INTERFERENCE EFFECTS ON LOCAL SCOUR AROUND BRIDGE PIERS

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By

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CERTIFICATE

It is certified that the work contained in the thesis entitled " **INTERFERENCE EFFECTS ON LOCAL SCOUR AROUND BRIDGE PIERS** ", by **GODDU PRASADA RAO** (Roll No. 9520301), has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

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SYNOPSIS

Location of bridges in close proximity, causes the upstream pier to interfere with the local scour around downstream bridge pier by creating wake and shedding of vortices. The interference of upstream pier wake and shedding of vortices modify the characteristics of horseshoe vortex which forms at the junction of pier and bed. Modification of horseshoe vortex will lead to increase or decrease in scour depths at downstream bridge pier.

Interference effect is defined as the ratio of the difference in local scour depths of upstream and downstream piers to the local scour depth of the upstream pier. If the interference effect is negative, i.e., local scour of down stream pier is more than upstream pier, the situation is considered dangerous. When the interference effect is positive, i.e. the downstream pier scour depth is less than upstream pier scour depth, the situation is considered safer. In the present work, this interference effect for different pier arrangements has been experimentally evaluated.

Experiments are conducted in two flumes with alluvial sand collected from river Ganges near Kanpur. Three types of arrangement pattern of piers are chosen. They are tandem arrangement (one behind the other), equilateral triangular arrangement and staggered arrangement. In staggered arrangements, two different arrangement patterns have been investigated. In pattern I, one pier is placed upstream and two piers downstream. In pattern II, two piers are placed on upstream side and one pier on downstream. In all the arrangement

patterns the flow situation was maintained near to the state of initiation of sediment motion, which is the state of flow in which maximum local scour occurs.

Interference effect is positive most of the times in tandem arrangement. In equilateral and staggered arrangement patterns, the interference effect takes positive and negative values. The maximum magnitude of negative interference is of the order of 0.2, which means the downstream pier scour depth is 20 percent more than upstream pier scour depth.

Length of negative interference effect zone along the centre line of spacing of piers extends almost nearly to the lateral spacing of piers. The magnitude of the maximum intensity of negative interference decreases with increase in lateral spacing of piers.

Effect of closeness in lateral spacing of piers in the absence of downstream piers results in increase in the magnitude of their scour depths due to lateral interference. The magnitude of maximum negative interference is of the order of 0.33, which means 33% increase in the scour depth of an isolated pier or pier without interference.

Wet paint impression studies indicate the growth of wake zone behind cylinders. For cylindrical piers side by side, the merging of wake zone is observed clearly. Wet paint impression studies gives the flow pattern on the rigid bed, when the piers are arranged in different patterns.

DEDICATED

To

Amma

and

Nanna

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G. P. R

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C_D	coefficient of drag
D	diameter of the cylindrical pier
d_{50}	median size of the sediment
Fr	Froude number
h	depth of flow
h_s	scour depth upstream of pier near to the stagnation point
h_{sd}	scour depth of downstream pier
h_{su}	scour depth of upstream pier
Q	discharge
R_D	pier Reynolds number
S	spacing of piers in equilateral triangular arrangement
U	mean velocity of flow
U_c	critical velocity of flow
X	spacing of piers in the direction of flow
Z	lateral spacing of piers perpendicular to the direction of flow

CHAPTER - I

INTRODUCTION

Rapid urbanisation and development of road transport and communication have caused construction of more and more bridges across rivers and waterways. The location of two parallel bridges in close proximity has drawn the attention of hyrdraulic Engineers concerned about their foundation stability. The hydraulic effect of bridge piers, located at short spacing involve interference of flow that results in scour depths different from that of an isolated pier.

Numerous investigations on depth of scour have been made in case of a single isolated pier having different shapes and flow conditions. Methods have been developed to predict the maximum scour depths at various conditions. However, the cause for the scour around bridge pier was eluding for a long time. Only recently it was pointed out that it is due to horseshoe vortex which is formed in the boundary layer separation of the flow on bed in front of the pier and it plays an important role in the scouring process. Some investigations on the process of scouring due to Horse-shoe vortex are carried out. There is very little knowledge available how the horse-shoe vortex gets modified when it comes under the interference of neighbouring piers. This knowledge is very essential in prediction of maximum scour depth, particularly when the pier is situated at the edge of the wake vortex of the upstream pier. Knowledge of the extent of scour depth is very important in safe and economical design of foundations of bridge piers. Under estimation of scour leads to failure, while over estimation will increase the cost of the structure. It becomes essential to investigate the extent of modification which occurs on maximum scour depth due to interference of piers. Interference effects depend on the geometry, arrangement pattern of the piers, location, size, shape, flow

conditions and the sediment characteristics. In the present investigation, it is planned to vary the geometry arrangement pattern of the pier location while keeping all other factors as constant. The geometry arrangement pattern includes the tandem arrangement, staggered arrangement and triangular arrangement.

The thesis is presented in five chapters as summarised below

CHAPTER - II

LITERATURE REVIEW

A large number of studies have been carried out to understand the cause of scour since last six decades. Some of the important studies are briefly described here as follows:

Keutner(1932) showed experimentally that local scour around a bridge pier is due to secondary flow generated as a result of lateral water surface slope developed by the obstruction of pier. Ishihara(1938) also showed that a secondary circulation created by the obstruction causes local scour. He attempted to develop an equation of scour force per unit width of the stream at the outer edge of the lateral water surface curvature (produced by the obstruction) in terms of centrifugal force and lateral water surface slope and for the point velocity variation along a vertical. Inglis(1949) also observed the vortex action involved in local scour in connection with his model studies on the Hardinge bridge pier. He argued that the greatest observed scour for obstructions of various types occurred at the nose of the pier was due to curved diving flow. Posey(1949, 1963), based on experimental studies, concluded that vortex motion is the cause of local scour around the obstruction. The size and strength of the scouring vortex were found to be dependent on the velocity distribution of the main flow and geometry of the space available. They also showed that the existence of a bottom spiral which excavated a large conical hole extending from the pier to a downstream dune.

Laursen (1951) showed that as the scour progressed, the separation vortex at the upstream face of the pier was intensified to the point of becoming the active scouring mechanism. Sediment was carried out of the scour hole by the spiral combination of the vortex along the sides of the pier.

Bata(1960) suggested that local scour at the bridge piers was due to the vertical velocity current which could be located at distances 1.5 to 2.0 D from the pier. The magnitude of such a velocity was about half the approach mean velocity. He found that Reynolds number and sediment size had very little effect on scour.

Tison(1961) considered the lateral curvature of stream lines near to be the cause of local scour based on model studies and the application of Bernoullie's equation. He emphasized that the maximum scour depth usually occurred at the nose of the pier where the curvature in the stream lines was maximum.

Melville(1975) found that a strong vertically downward flow is developed ahead of cylinder as the scour hole enlarged. The size and strength of the vortex increased rapidly and the velocity near the bottom of the hole decreased as the scour hole enlarged. The magnitude of the downward flow appeared to be directly associated with the rate of scour. The rate of increase of vortex strength decreases as the scour hole developed.

2.1 Scour depth prediction methods

Various prediction formulae for local scour around bridge piers proposed by researchers have been summarized by Breusers(1977), Melville(1988), and Garde (1989). The different approaches used in scour depth prediction formulae may be broadly put into two categories

2.2 Empirical Methods

(A) Regime method: A formula for the estimation of the maximum scour depth around an isolated bridge pier, based on Lacey's regime flow equation with the support of field data taken at Hardinge bridge over the Ganges river and the model experiments of Inglis at Poona laboratory, was proposed in 1949 as $h_s = 0.473(Q/f)^{1/3}$, where h_s is the scour depth, Q = discharge; f = silt factors

The Indian Railways have adopted this formula to estimate the maximum scour depth measured from the water surface to the bottom of the scour hole as twice the Lacey's regime depth. It is obvious from the formula that parameters like pier geometry and flow depth are unimportant. Regime approach includes formulae given by various investigators such as Breusers, Jain and Modi. However, the regime approach only tends to concentrate on overall dimensions. The approach does not reveal the internal mechanism involved in a scouring process. The regime equation, originally derived for straight reaches of channels in equilibrium for parallel flow conditions, are not applicable to flow condition at bends and obstructions where the flow is mainly characterised by large scale curvatures, separation, vortex formation, microturbulence and energy dissipation.

(B) Rational method: The rational method is based on the concept that the tractive force exerted by flowing water on the bed particles is mainly responsible for the motion of the bed material when its value exceeds the critical limits. Based on this concept, the equilibrium scour depth in long channel constructions have been predicted by various investigators like Straub(1934), Knezvic(1960), Bata(1960), Garde(1961), Chabert(1956), Hanco(1971), Breusers(1977) etc.

Laursen has proposed design curve and empirical relations for maximum scour depth measured from bed level which identify pier geometry, angle of attack and upstream flow depth as the important variables. Jain and Modi made comparative studies of the existing scour formulae, and they conclude that the scour depth formula by Laursen and Toch, is the best predictor, as it envelops all data and predicts less than other formulae. It may be noted that the Laursen formulae for the scour depth do not involve sediment size effect. Quite similar to the formula of Laursen and Toch, another formula containing the effect of sediment size on scour depths were proposed by Jain and effect of sediment size on maximum scour depth was verified by experimental studies by various authors like Chee, Melville, Raudkivi and Ettema etc.

2.3 Factors Governing the Scour Depth Around an Isolated Pier

The factors which govern the scouring near the isolated pier are described below

(A) Effect of approach velocity: U/U_c, U is the average velocity and U_c is the critical velocity at which initiation of sediment motion occurs on flat bed.

(a) $U/U_c \leq 0.5$ - No scour

(b) $0.5 \leq U/U_c \leq 1.0$ - clear water scour. In this some investigators found that the scour depth increases linearly with velocity. They showed that the clear water scour approaches equilibrium asymptotically, over a period of days where as the live bed scour develops rapidly and its depth fluctuates in response to the passage of bed features.

(c) $U/U_c \geq 1.0$ - The scour will take place due to the sediment motion with the formation of ripples, known as live- bed scour conditions. The scour depth is dependent on time factor.

(B) Effect of shape of the pier: The shape of pier has great influence on scour depth relations, giving scour depth as the function of pier diameter (D), are as follows:

(a) Larras : $h_s = 1.05(D)^{0.75}$

(b) Shen : $h_s = (D)^{0.619}$ for constant U.

(c) Breusers : $h_s = 1.4D$ for circular piers.

The investigators whose work contributed to the above formulas are Tison(1940), Posey(1949), Laursen and Toch(1956), Bata(1960), Roper and others(1967). They classified piers shapes into two categories :

(i) Blunt-nosed pier, where a strong Horse-shoe vortex system develops and thus causes maximum scour depth at the pier nose. The length of the pier and downstream pier shape should have minimum effect if the blunt - nosed pier is aligned with flow.

(ii) Sharp nosed pier: Here the Horse - shoe vortex system is very weak and the maximum scour depth occurs near the down stream end. Therefore, the effect of pier shape is significant in scour.

(C) Effect of flow depth: The scour depth becomes independent of flow depth, when flow depth is greater than three times the pier diameter, i.e., h/D>3.0, the influence of this parameter can be neglected. The relations give scour depth as a function of regime water depth.

Example: Lacey and Inglis : $h_s = 0.473(Q/f)^{1/3}$ MKS units,

where Q = discharge

f = Silt factor

2.4 Mechanism of Local Scour Around Isolated Bridge Piers

The large scale eddy structures or the system of vortices developing around the pier is a characteristic feature of flow near the pier. These vortex systems are considered to be the basic mechanisms of local scour which has long been recognised by the investigators such as Tison(1940), Keutner(1932), Posey(1949), Laursen and Toch(1956), Neill(1964), Bata(1960), Roper(1967), Melville(1975), Baker(1979 & 1980), Gupta(1984), Shah(1988) and Mazzamil(1992).

Roper described in detail that the eddy structure may be composed of the Horse-shoe vortex system, wake vortex system and trailing vortex system, depending upon the type of pier and free stream conditions. The vortex systems are an integral part of flow and strongly affect the vertical component of the velocity head of the pier. They further described the mechanics of each type of vortex system which are given below

The Horse-shoe vortex system is formed when the vortex filaments, transverse to the flow in two-dimensional undisturbed velocity field, are concentrated by the presence of blunt- nose pier. The concentration is accomplished by the non-uniform pressure field induced by pier boundary. If the pressure field is sufficiently strong, it causes a three- dimensional separation of boundary layer which in turn, rolls up ahead of pier to form Horse-shoe vortex system. The wake vortex system is formed by rolling up of unstable shear layers generated at the surface of pier, and which are detached from either side of the pier at the separation line. At low Reynolds numbers ($4 < Re_p < 50$), these vortices are stable and form a standing system down stream close to the pier. For higher Reynolds numbers of practical interest, however the system is unstable, and the vortices are shed alternately from the pier and convected downstream. The strength of the vortices in the wake system varies greatly depending on the pier shape and fluid velocity. A stream lined pier will create a relatively weak wake, but a blunt body produces a strong one. The wake vortex system acts some what like a vacuum

cleaner in removing the bed material. The bed material is carried downstream by the eddies shedding from the pier. The trailing-vortex system is formed when finite pressure difference exist between two surfaces meeting at a corner, such as the top of the pier. It is composed of one or more discrete vortices attached to the top of the pier and extending downstream. It usually occurs only on completely submerged piers.

2.5 Interference Effects of Multiple Piers on Local Scour

Local scour at a bridge pier is influenced by nearby piers. Studies on this aspect of local scour reported in literature are reviewed here.

Timonoff(1911) performed a model study to investigate the importance of streamwise spacing of bridge piers in the case of parallel bridges. Based on the observed sheltering effect of upstream pier on the downstream pier he recommended that new bridge piers should be located in close proximity of old piers and axially aligned.

Tison(1940) carried out a model study to investigate the lateral spacing of piers, placed in side by side arrangement, on scour depths . He found no mutual interference on maximum scour depth for $Z_c / D \geq 4.3$, where Z_c is the lateral spacing of piers measured from centre to centre .

Dietz (1973) made a study of the angle of attack(θ) on maximum scour depths around laterally separated circular piers. He concluded that scour depth is not influenced by θ for $Z_c /D \geq 3$.The interference effect on scour depths at piers in various arrangements as reported by Hannah were as follows:

(A) Piers in tandem arrangement (angle of attack 0^0)

The scour depth at the front pier is the same as for the single pier at $X_c/D = 1$. As the separation between the piers increases, the scour depth also increases upto $X_c /D = 11$ maximum occurs at $X_c/D = 2.5$ due to reinforcing effect. For larger spacing, the scour depth is same as for a single pier. The scour at the rear pier is due to sheltering effect. At $X_c/D = 1$, the sheltering effect is complete with the two piers acting as one entity. The maximum scour depth in the resultant scour hole occur at the front pier with the scour depth at the rear pier being only 87% of the maximum. As the separation increases, the sheltering effect reduces

and at $X_c/D = 2$, a Horseshoe vortex forms around the rear pier and increases in strength with separation . Thereafter vortices shed from the front pier pass close enough to the rear pier to aid scouring. The scour depths at rear pier thus increase with separation, reach maximum at $X_c/D = 6$. At larger spacing, scour depth reduces as a result of decrease in vortex shedding effect and attain a maximum at $X_c/D = 17$. With further separation, only the wake sheltering remains and this too progressively weakens.

(B) Side by side arrangement

Interference effects resulting in increased scour depths have been always observed for lateral spacing less than some limiting spacing, variously reported between 3D to 8D. Beyond this limiting spacing, no effect of one pier on its neighbouring pier scour depth was observed.

(C) Staggered arrangement

Hannah(1978) showed that the front pier scour depth is far less sensitive to the angle of attack compared to the rear pier scour depth. The latter increases from h_s/h_{si} 0.95 at $\theta = 0^0$ to around $h_s/h_{si} = 1.2$ at $\theta = 45^0$,and then starts decreasing, where h_{si} is the depth of scour for an isolated pier.

2.6 Statement of Problem

The aim of present study is to quantify the magnitude of interference on local scour depth of piers for different arrangement patterns. The arrangement pattern of the piers consists of tandem arrangement and staggered arrangement. The details of arrangement are given below:

In order to achieve this aim, the present investigation has been carried out in three phases. In the first phase of investigation, the piers are located in tandem arrangement in the flume at different spacing(X/D = 0, 1, 2, 3, 4, 5 , 6, 7 , 8, 9, 10, 12, 14, 16, 18, 20, 24, 28 and 32) and for different flow conditions($Fr = 0.16$ to 0.19).

In the second phase, the piers are kept in staggered arrangements (one pier on the upstream side and two piers on downstream side) and for different flow conditions($Fr = 0.17$ to 0.19). The arrangement patterns are as follows:

(a) Equilateral spacing (X/D = 1, 2, 3, 4, 5 and 7)

(b) X = 5D (Z/D = 1, 2, 3, 4 and 5)

(c) X = 10D(Z/D = 1 ,1.5, 2, 3, 4, 5and 6)

(d) X = 15D(Z/D = 1, 2, 3, 4, 5 and 6)

(e) X = 20D(Z/D = 1, 2, 3, 4, 5, 6 and 7)

(f) X = 25D(Z/D = 1, 2, 3, 4, 5, 6, 7, and 8)

(g) X = 30D(Z/D = 1, 2, 3, 4, 5, 6, 7 and 8).

In the third phase, piers are kept in staggered arrangements(two piers on upstream side and one pier on downstream side) and for different flow conditions (Fr = 0.11 to 0.17). The arrangement pattern are as follows:

a) Z = 2D(X/D = 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 14, 18, 22, 26 and 30)

b) Z = 4D(X/D = 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 14, 18, 22, 26, 30, 34, 38, 42, 46 and 50).

c) Z = 6D(X/D = 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 14, 18, 22, 26, 30, 34 and 38)

d) Z = 8D(X/D = 1, 2, 3, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, 28, 30, 32, 34, 36, 38, 40, 42, 44, 46 and 50.

CHAPTER - III

EXPERIMENTAL METHODS

3.1 Introduction

Experiments have been conducted to determine dynamic and static scour depth around bridge pier models in laboratory flumes having movable beds. The magnitudes of dynamic scour depths and scour profiles hope to reveal the interference effects of bridge piers located at proximate distance to each other.

3.2 Experimental Setup

Details of Flume - A

Experiments were conducted in a flume - A of 450 cm length, 106 cm width, and 58 cm depth. The flume bed composed of alluvial sand (d_{50}=0.16mm and Standard deviation σ_g=1.688), collected from river Ganges near Kanpur. The flume was used for measurement of interference effects of piers arranged in tandem arrangement and staggered arrangement, and the three piers are located in equilateral triangular pattern. Water was supplied from a overhead tank through a pipe. For all sets of experiments, depth of flow was 9.6cm and average velocity in the flume was 0.17m/s . The flow conditions were maintained such that the state of sediment bed was slightly above the initiation of sediment motion condition. The

test station was located at 3.35 m from the inlet. The glass cylindrical pier of 5cm diameter, 50cm in length with top end open and bottom end conical in shape was used as pier model.

Details of Flume - B

In tandem arrangement, piers were located one behind the other in the direction of flow. Experiments on staggered arrangement pattern were carried out in flume-B. Flume-B is a recirculating flume which is 23m in length, 0.90m wide and 0.60m in depth. The alluvial sand collected from the bed of the river Ganga at Kanpur was used as the sediment. The median size of the sediment as reported already was 0.16mm and geometric standard deviation was 1.688. The flume-B runs with a pump attached at the end of the flume with a standby connected in parallel. The discharge was measured with the help of a Venturimeter connected to the circulating pipes. The test section was located at 16m from the inlet of the channel, so as to have a fully developed flow towards the test section.

i. Tandem arrangement

Piers were located centrally in the flume at varying longitudinal spacing X/D = 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 14, 16, 18, 20, 24 ,28 and 32 for tandem arrangement. For staggered arrangement , one cylindrical pier was kept at upstream and two piers was located at different distances Z/D = 1, 2, 3, 4, 5, 6, 7, 8 at X/D = 5, 10, 15, 20, 25, 30. At a time there were three piers one at upstream and two at downstream in staggered position. Details of arrangement are shown in Figure 3.1(a). Here Z is lateral clear spacing between two piers X is longitudinal clear spacing between piers in flow direction, D is the diameter of pier.

ii. Equilateral triangular arrangement pattern

Piers were arranged in the triangular arrangement having equilateral pattern. The arrangement is shown in Figure 3.1(b). The spacing(S) between them was maintained constant. The value of S/D = 0, 1, 2, 3, 4, 5 and 7 was varied in all cases, where S is the spacing between piers forming the side of equilateral triangle. The Froude number of flow was kept constant at 0.18. Piers were vertically fixed in alluvial sediment bed projecting well above the water surface. In staggered arrangement, there were two patterns as shown in Figure 3.1(c) and (d).

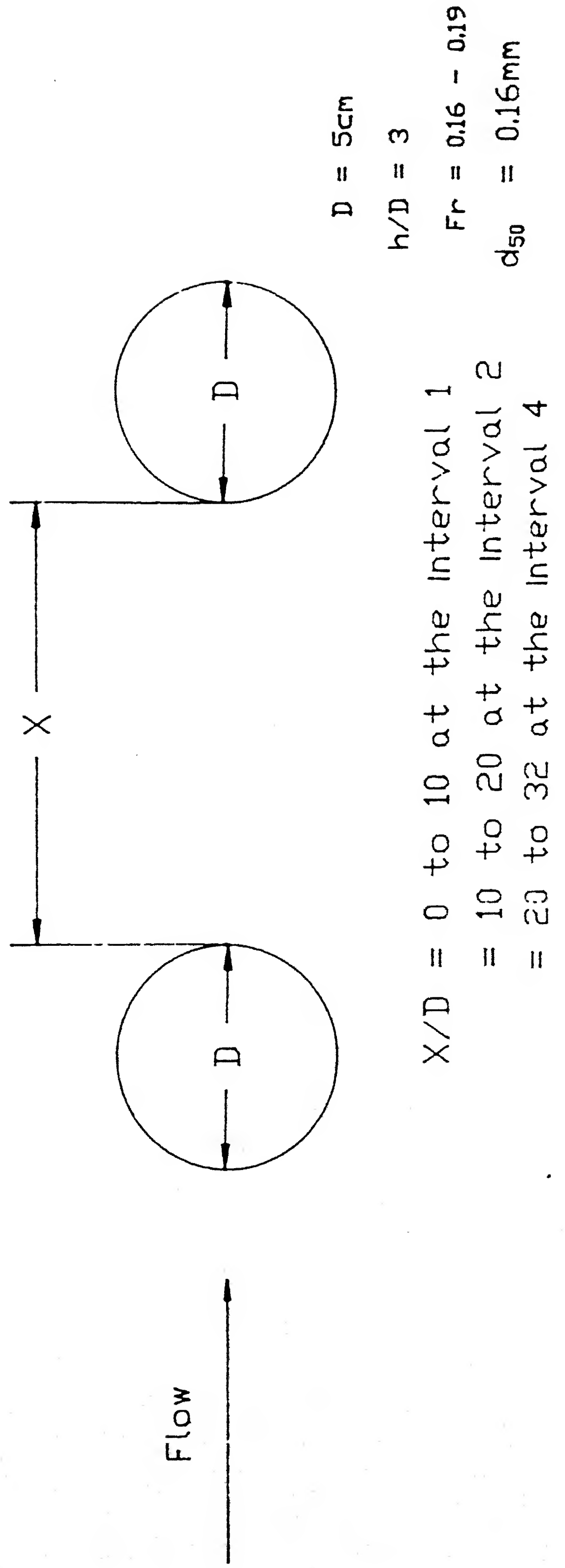
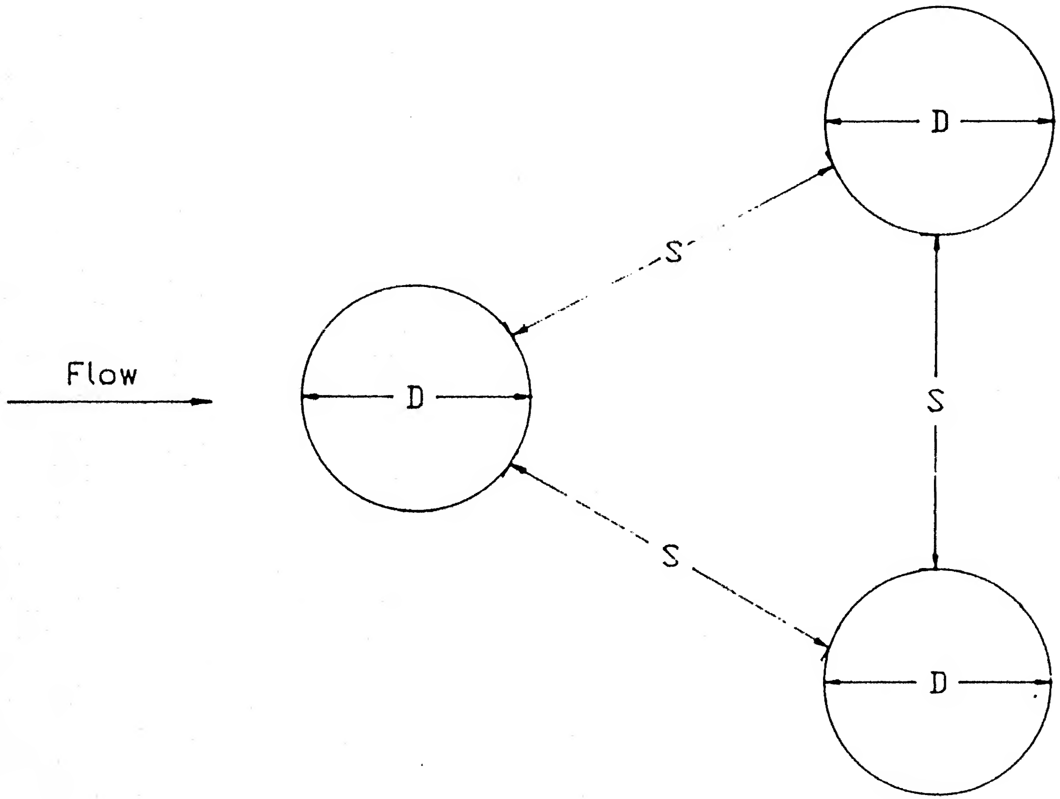


Fig: 3.1a Tandem Arrangement



$D = 5cm$
$h/D = 2.0$
$Fr = 0.17 - 0.18$
$d_{50} = 0.16mm$
$S/D = 1, 2, 3, 4, 5$ and 7

Fig 3.1b Equilateral Triangular Arrangement

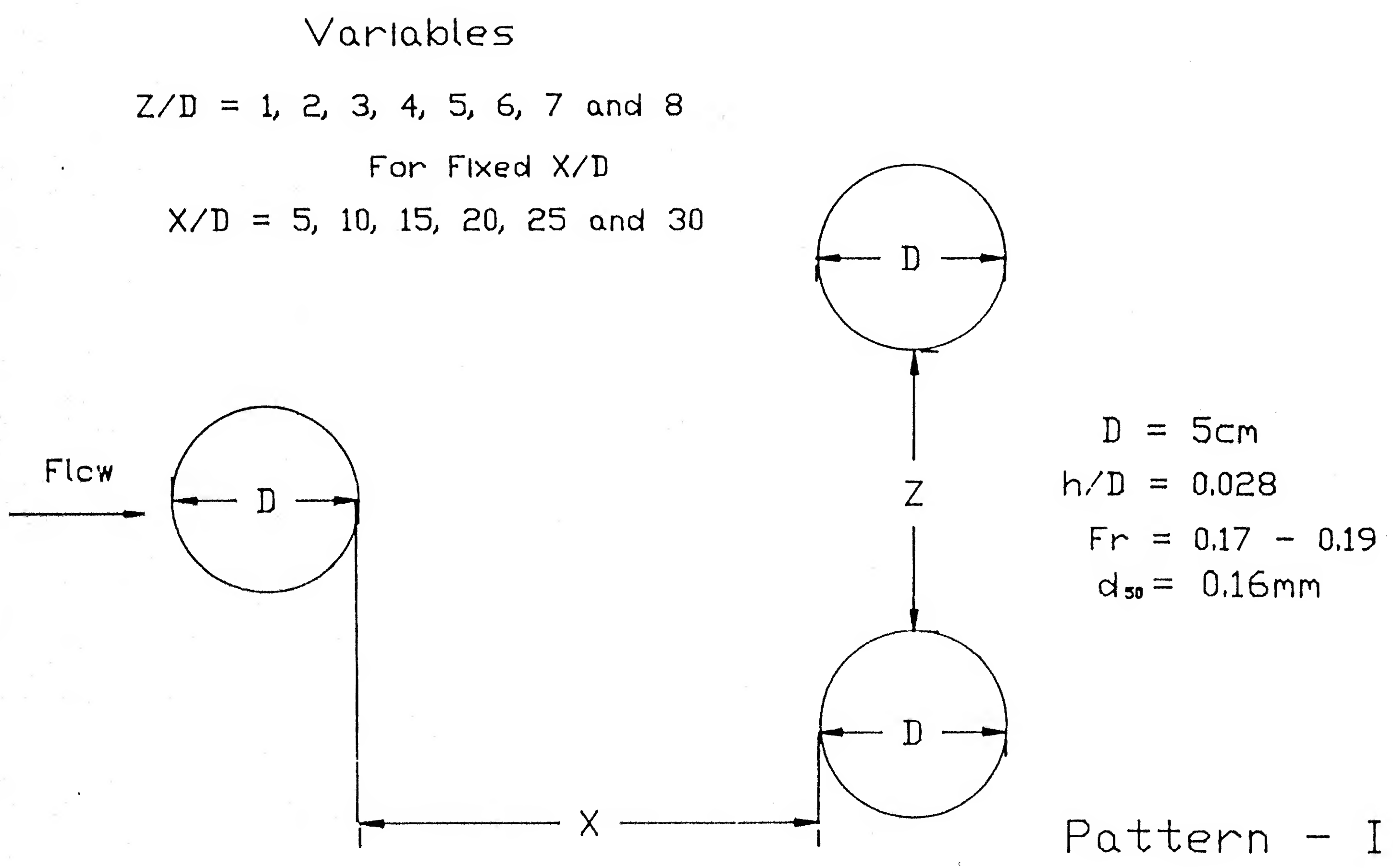
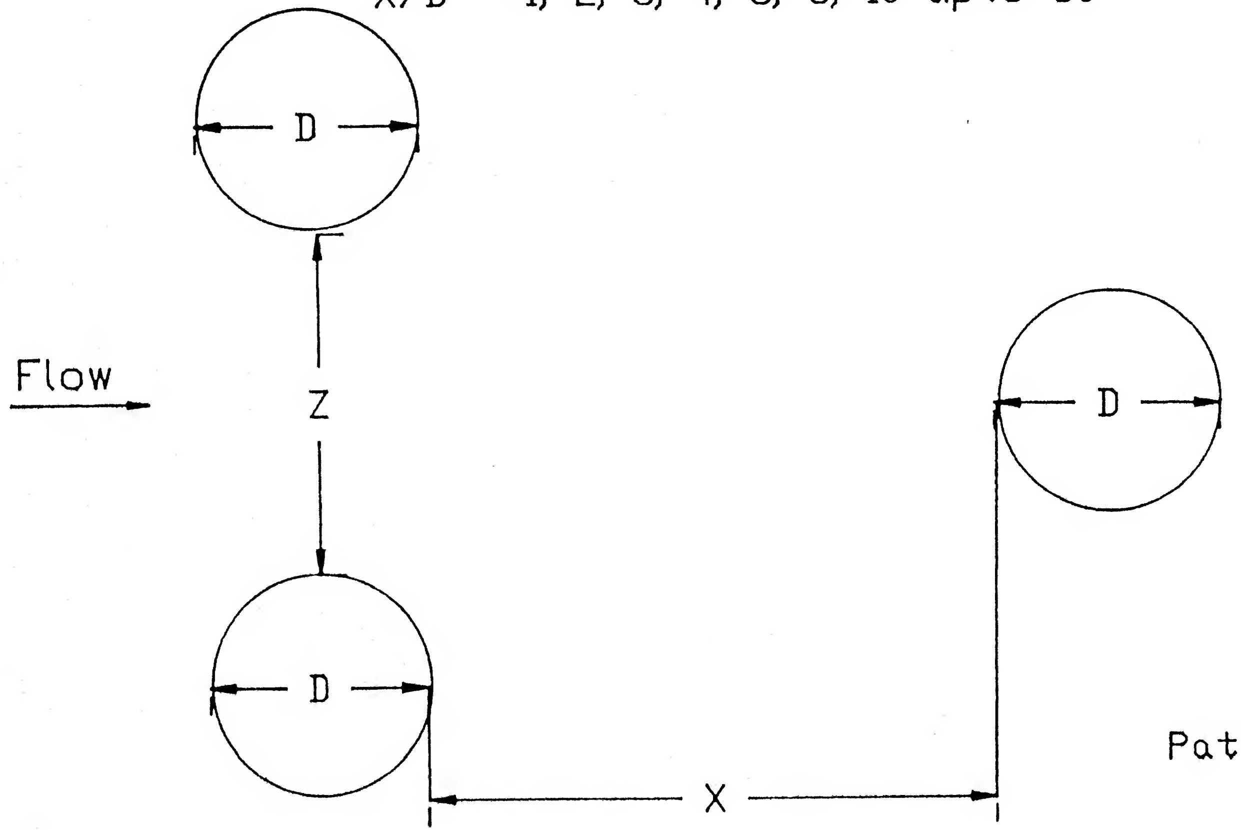


Fig. 3.1c One Pier Upstream and Two Piers Downstream

Z/D = 2, 4, 6 and 8

X/D = 1, 2, 3, 4, 6, 8, 10 upto 50



D = 5cm
h/D = 3.68
Fr = 0.11 - 0.19
d_{50} = 0.16mm

Pattern - II

Fig: 3.1d Two Piers Upstream and One Pier Downstream

iii. Staggered arrangement pattern

For another type of staggered arrangement, where two piers were placed at upstream and Z/D =2, 4, 6 and 8. The third pier was placed along the central line of spacing in the direction of flow in the downstream direction at X/D = 2 ,3, 4, 5, 6, 7, 8, 10, 12, 14, 18, 22, 26, 30, 34, 38, 42, 46 and 50. The depth of flow and velocity of water in the flume was 18cm and 0.165 m/s respectively. The Froude number of flow was 0.12. The sediment used was again alluvial sediment collected from river Ganges near Kanpur. The size distribution is shown in the Figure 3.2

Details of experimental procedure

Before starting the flow, the sediment bed was leveled and gradually water was allowed to flow in the flume. When the flow reached the equilibrium state of the required condition, the bed levels were measured at places where the piers are supposed to be located. After setting the flow for 30 minutes, the upstream pier was inserted at the position marked for its and then immediately downstream pier or piers were inserted into the sediment bed appropriately at their marked positions. As soon as the piers were inserted into the sediment bed, scour started developing around the pier. The scour depth on the line of symmetry of the flow at the front stagnation position was measured at the intervals t = 1, 5, 10, 15, 20, 30, 40, 50, 60, 80, 100, 150, 200, 250, 300, 350, 400, 500 and 600 minutes. At the end of 600 minutes, scour profiles were measured at 0°, 60° and 90°. The depth of flow upstream of the piers was measured and its corresponding discharge was measured over the weir.

When the flow was stopped, the bed was allowed to settle down. Next day the static scour profiles were measured at positions where dynamic profiles were measured on previous day. After this measurement of static profiles, the sediment bed was leveled and the flume was ready for the next experiment to be conducted. This procedure was adopted in all the experiments.

Wet Paint Impression Technique :

This technique was used for flow visualisation studies on the rigid bed. The flume in which paint - impression studies were carried out was of length 4.6m and 0.155m width.

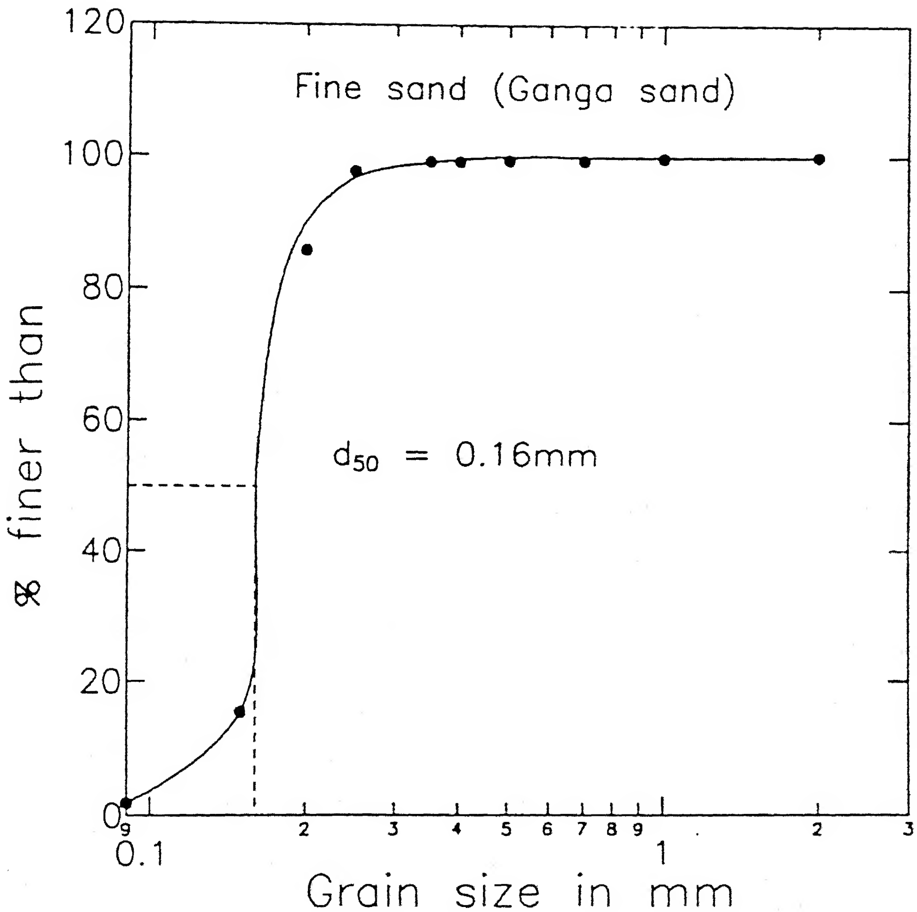


Fig: 3.2 Grainsize Distribution

Experimental Procedure :

The base plate to which pier was attached, was thoroughly cleaned and a thin coat of a base paint preferably white was given and was allowed to dry for several hours. There after, oil paint of required consistency, prepared by mixing a little quantity of thinner to commercially available paint, was spread by painting brush.

The flow was maintained in the flume to the required velocity and depth. Then the above plate was kept in it carefully to avoid paint flow in any direction due to its tilt. The paint started to move under the effect of shear stresses on the bed, thus the formation of impressions of flow patterns on the base plate. The plate had to be in this state for 2-5 hours of duration till the paint thinned down to a stage of no further movement.

Then the flow was stopped in the flume and the plate was taken out and allowed to dry with a warm air blower so that water drops evaporate. The streak lines could be photographed, photocopied or traced to keep a permanent record of the impressions on the bed. The plate, in dry state with distinct flow impressions on bed could be used for analysis.

Wet paint impressions showing the separation zone around circular cylindrical pier of diameter 2.5cm and height 19.25cm are obtained for a single cylinder placed at the centre of the plate. This gives the details of wake development behind a circular cylinder. The cases for two cylindrical piers spaced laterally at Z/D = 2, 4, 6, 8 were studied to know the merging of the wakes and growth of wake zone in the downstream direction. Positioning of the cylinders are shown in Figure 3.1(e). The dimensions of two cylindrical piers was 1.0cm diameter and height was 19cms. The dimensions of the plate were 71cm long and 15cm wide. The cylindrical piers were installed vertically on the plate at a distance of 16.5cm. The plate was positioned on the bed of the flume at a distance of 2.6cm from the inlet.

The tables containing the details of experimental flow conditions and scour depths at the end of 600 minutes are given as follows

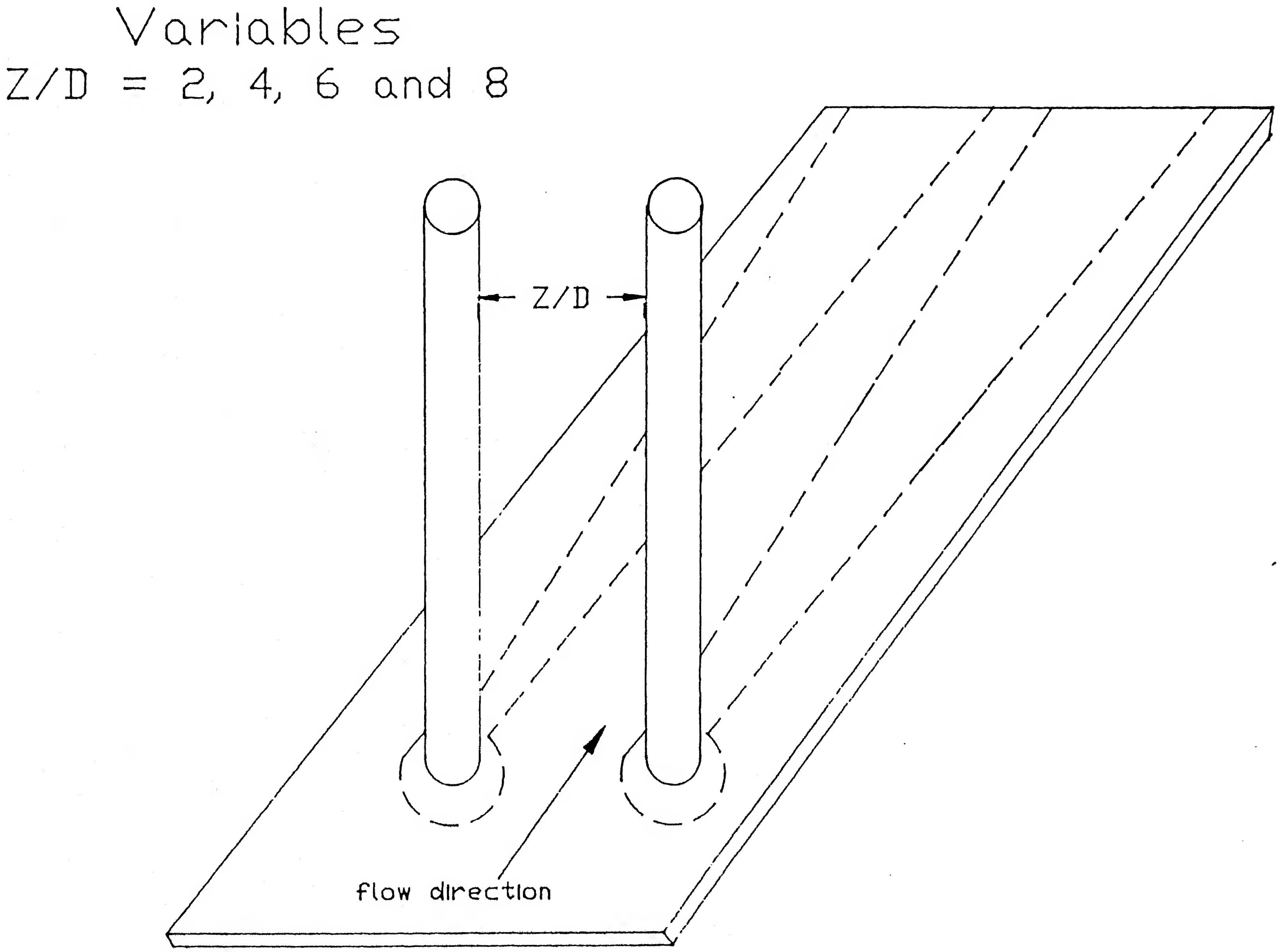


Figure 3.1e : Positioning of cylinders in wet paint impression studies

3.3 Details of Data Collected

TANDEM ARRANGEMENT PATTERN
TABLE - 3.1

U/S pier diameter = 5cm D/S pier diameter = 5cm

Spacing X/D	Depth of flow(h) m	Discharge (Q) m^3/sec	Froude number (Fr)	hsm(u/s) cm	hsm(d/s) cm
0	0.109	0.01929	0.16	5.25	4.15
1	0.109	0.01921	0.16	5.25	4.10
2	0.106	0.01921	0.17	4.6	4.25
3	0.099	0.01881	0.18	4.25	4.25
4	0.105	0.01910	0.17	4.55	4.30
5	0.106	0.01851	0.16	4.85	4.25
6	0.104	0.01875	0.17	4.90	4.20
7	0.105	0.01916	0.17	5.00	4.10
8	0.109	0.02013	0.17	4.05	3.95
9	0.109	0.01922	0.16	4.25	3.90
10	0.106	0.01920	0.17	4.45	3.90
12	0.104	0.01920	0.17	4.55	3.95
14	0.098	0.01926	0.19	4.65	4.00
16	0.097	0.01910	0.19	4.50	4.10
18	0.097	0.01854	0.18	4.90	4.15
20	0.097	0.01850	0.18	4.50	4.25
24	0.989	0.01850	0.18	4.50	4.25
28	0.102	0.01840	0.17	5.25	4.20
32	0.102	0.01840	0.17	4.85	4.15

EQUILATERAL TRIANGULAR ARRANGEMENT

TABLE - 3.2

1- h_{sm} (u/s) 2- h_{sm} (d_L/s) 3- h_{sm} (d_R/s)

Spacing (S/D)	Pier No	Depth of flow(h) m	Discharge (Q) m^3/sec	Froude number (Fr)	h_{sm} cm
0.0	1	0.0942	0.0186	0.18	4.95
	2	0.0942	0.0186	0.18	5.30
	3	0.0942	0.0186	0.18	5.35
1.0	1	0.0961	0.0188	0.18	6.40
	2	0.0961	0.0188	0.18	6.35
	3	0.0961	0.0188	0.18	6.30
2.0	1	0.0970	0.0188	0.18	5.85
	2	0.0970	0.0188	0.18	5.10
	3	0.0970	0.0188	0.18	5.25
3.0	1	0.1038	0.0188	0.17	4.85
	2	0.1038	0.0188	0.17	3.85
	3	0.1038	0.0188	0.17	4.05
4.0	1	0.1042	0.0194	0.17	4.90
	2	0.1042	0.0194	0.17	4.65
	3	0.1042	0.0194	0.17	4.75
5.0	1	0.1029	0.0196	0.18	4.65
	2	0.1029	0.0196	0.18	4.55
	3	0.1029	0.0196	0.18	4.45
7.0	1	0.1025	0.0194	0.18	4.55
	2	0.1025	0.0194	0.18	4.35
	3	0.1025	0.0194	0.18	4.55

STAGGERED ARRANGEMENT, PATTERN - I

TABLE - 3.3 A

Spacing X/D = 5

Z/D	Depth of flow(h) m	Discharge (Q) m^3/sec	Froude number (Fr)	h_{sm} (u/s) cm	h_{sm} (left) cm	h_{sm} (right) cm
1.0	0.1017	0.0191	0.18	4.95	4.90	4.85
1.5	0.0970	0.0191	0.18	5.70	5.10	5.00
2.0	0.0962	0.0190	0.19	5.00	4.95	4.80
3.0	0.097	0.0193	0.19	4.90	4.90	4.85
4.0	0.0962	0.0190	0.19	4.95	4.95	4.85
5.0	0.0968	0.0195	0.19	4.90	5.00	5.10

TABLE - 3.3 B

Spacing X/D = 10

Z/D	Depth of flow(h) m	Discharge (Q) m^3/sec	Froude number (Fr)	h_{sm} (u/s) cm	h_{sm} (left) cm	h_{sm} (right) cm
1.0	0.1014	0.01924	0.18	5.40	5.30	5.40
1.5	0.1013	0.01948	0.18	5.40	5.30	5.35
2.0	0.0996	0.01934	0.18	4.95	4.95	5.30
3.0	0.0990	0.01934	0.18	5.40	4.50	4.85
4.0	0.0976	0.01899	0.19	5.45	5.20	5.30
5.0	0.1010	0.01916	0.18	5.45	4.90	5.30
6.0	0.0988	0.01899	0.18	5.25	4.95	5.25

TABLE - 3.3 C

Spacing X/D = 15

Z/D	Depth of flow(h) m	Discharge (Q) m^3/sec	Froude number (Fr)	h_{sm} (u/s) cm	h_{sm} (left) cm	h_{sm} (right) cm
1.0	0.0978	0.01894	0.19	5.30	5.15	5.65
1.5	0.1024	0.01910	0.18	5.15	5.10	5.20
2.0	0.1007	0.01894	0.18	4.90	5.00	5.00
3.0	0.1018	0.01905	0.18	5.45	4.95	5.05
4.0	0.1020	0.01870	0.17	5.40	5.00	5.15
5.0	0.1035	0.01905	0.17	5.45	4.90	4.95
6.0	0.1024	0.01881	0.17	5.55	4.95	5.00

TABLE - 3.3 D

Spacing X/D = 20

Z/D	Depth of flow(h) m	Discharge (Q) m^3/sec	Froude number (Fr)	h_{sm} (u/s) cm	h_{sm}(left) cm	h_{sm} (right) cm
1.0	0.1006	0.01934	0.18	4.95	4.80	5.05
2.0	0.1021	0.01916	0.18	5.00	4.85	5.00
3.0	0.1010	0.01908	0.18	5.05	4.80	4.90
4.0	0.1024	0.01881	0.18	5.15	4.70	4.95
5.0	0.1025	0.01899	0.17	5.25	4.60	4.75
6.0	0.1016	0.01841	0.17	5.20	4.65	4.70
7.0	0.1020	0.01850	0.17	5.20	4.70	4.75

TABLE - 3.3 E

Spacing X/D = 25

Z/D	Depth of flow(h) m	Discharge (Q) m^3/sec	Froude number (Fr)	h_{sm} (u/s) cm	h_{sm}(left) cm	h_{sm} (right) cm
0.5	0.1020	0.01880	0.18	5.70	5.25	5.15
1.0	0.1014	0.01894	0.18	5.70	5.25	5.25
2.0	0.098	0.01664	0.17	5.75	5.35	5.25
3.0	0.1018	0.0191	0.18	5.25	5.20	5.35
4.0	0.0991	0.0187	0.18	5.65	5.15	5.20
5.0	0.102	0.01894	0.17	5.55	5.20	5.35
6.0	0.1015	0.01894	0.18	5.60	5.25	5.30
7.0	0.1072	0.01929	0.17	5.80	5.30	5.30
8.0	0.106	0.01921	0.17	5.60	5.30	5.35

TABLE - 3.3 F

Spacing X/D = 30

Z/D	Depth of flow(h) cm	Discharge (Q) m^3/sec	Froude number (Fr)	h_{sm} (u/s) cm	h_{sm} (left) cm	h_{sm} (right) cm
1	0.1010	0.01921	0.18	4.95	5.35	5.50
2	0.1015	0.01910	0.18	4.90	5.40	5.45
3	0.1020	0.01894	0.17	4.80	5.10	5.25
4	0.1005	0.01855	0.17	5.05	5.00	5.30
5	0.1020	0.01894	0.17	5..15	5.10	5.20
6	0.1012	0.01894	0.18	5.00	4.95	5.15
7	0.0990	0.01881	0.18	4.95	4.95	5.15
8	0.0995	0.01881	0.18	5.20	5.00	5.10

STAGGERED ARRANGEMENT, PATTERN - II

TABLE - 3.4A

Spacing (Z/D = 2)

X/D	Depth of flow (h)	Discharge	Froude number	h_{sm} (left)	h_{sm} (right)	h_{sm} (d/s)
1	0.171	0.0298	0.150	7.50	7.60	7.70
2	0.175	0.0298	0.145	6.02	7.05	7.82
3	0.172	0.0299	0.150	6.61	7.66	7.95
4	0.176	0.0299	0.143	6.31	6.36	5.21
5	0.182	0.0299	0 .136	5.97	6.12	4.57
6	0.181	0.0290	0.137	6.35	6.50	5.10
7	0.170	0.0298	0.150	6.98	7.20	5.98
8	0.175	0.0300	0.145	6.90	7.70	6.05
9	0.177	0.0299	0.142	6.10	7.25	5.95
10	0.175	0.0298	0.145	7.06	7.71	6.01
12	0.180	0.0299	0.139	6.40	6.90	6.15
14	0.175	0.0299	0.145	6.85	7.25	5.78
18	0.182	0.0299	0.137	5.80	6.40	5.15
22	0.173	0.0299	0.146	6.18	6.70	5.05
26	0.178	0.0299	0.141	6.28	6.03	4.85

STAGGERED ARRANGEMENT, PATTERN - II

TABLE - 3.4 B

Spacing Z/D = 4

X/D	Depth of flow(h)	Discharge	Froude number	h_{sm} (left)	h_{sm} (right)	h_{sm} (d/s)
2	0.189	0.02887	0.13	5.80	7.25	6.70
3	0.200	0.02933	0.12	5.35	5.60	5.75
4	0.204	0.02796	0.11	5.45	5.95	6.10
5	0.196	0.02963	0.12	5.35	5.45	6.10
6	0.200	0.02885	0.12	4.40	5.00	5.95
7	0.184	0.02898	0.13	5.35	5.25	5.90
8	0.180	0.03008	0.13	4.95	5.40	5.55
9	0.182	0.02971	0.13	5.45	5.85	5.70
10	0.180	0.02939	0.13	5.15	5.60	5.90
12	0.184	0.02950	0.13	4.70	4.95	5.45
14	0.191	0.02940	0.12	4.85	5.80	6.45
18	0.177	0.02890	0.13	5.75	6.45	6.80
22	0.182	0.02940	0.13	5.60	6.05	5.85
26	0.178	0.02950	0.13	5.45	6.30	5.75
30	0.173	0.02990	0.14	5.65	6.15	5.95
34	0.192	0.02980	0.13	5.70	6.55	5.60
38	0.174	0.02990	0.14	5.80	6.65	5.80
42	0.162	0.03000	0.16	6.70	7.00	5.85
46	0.168	0.02970	0.15	6.10	6.65	5.35
50	0.193	0.02960	0.12	6.05	6.35	4.8

STAGGERED ARRANGEMENT, PATTERN - II

TABLE - 3.4 C

Spacing Z/D = 6

X/D	Depth of flow (h)	Discharge	Froude number	h_{sm} (left)	h_{sm} (right)	h_{sm} (d/s)
1	0.175	0.0299	0.14	6.05	6.35	7.05
2	0.144	0.0296	0.19	6.40	6.50	7.05
3	0.178	0.0298	0.14	6.60	6.05	7.30
4	0.170	0.0303	0.15	6.65	6.45	7.20
5	0.173	0.0298	0.15	6.30	6.35	7.25
6	0.165	0.0299	0.16	6.60	6.50	6.75
7	0.173	0.0300	0.15	6.55	6.40	6.90
8	0.176	0.0298	0.14	7.20	7.30	7.15
9	0.159	0.0298	0.17	6.90	6.95	6.95
10	0.160	0.0300	0.17	7.45	6.80	5.90
12	0.160	0.0299	0.16	7.35	6.60	6.55
14	0.164	0.0299	0.16	7.35	6.85	7.35
18	0.176	0.0298	0.14	6.95	6.55	6.65
22	0.173	0.0298	0.15	6.50	6.55	6.45
26	0.186	0.0299	0.13	6.25	6.30	6.75
30	0.178	0.0299	0.14	6.05	5.90	6.40
34	0.181	0.0298	0.14	6.80	6.65	6.15
38	0.178	0.0298	0.14	6.70	6.45	6.15

STAGGERED ARRANGEMENT, PATTERN - II
TABLE - 3.4 D

Spacing Z/D = 8

X/D	Depth of flow (h)	Discharge	Froude number	h_{sm} (left)	h_{sm} (right)	h_{sm} (d/s)
1	0.176	0.0299	0.14	5.74	6.44	6.54
2	0.180	0.0298	0.14	5.35	6.95	7.20
3	0.177	0.0299	0.14	6.20	7.20	7.70
4	0.178	0.0298	0.14	5.10	6.49	6.64
6	0.180	0.0298	0.14	5.29	6.56	6.99
8	0.178	0.0298	0.14	5.95	6.70	6.60
10	0.172	0.0297	0.15	4.21	6.31	6.55
12	0.175	0.0298	0.14	5.82	6.32	5.87
14	0.176	0.0297	0.14	6.45	6.25	6.65
16	0.186	0.0298	0.13	5.90	5.25	6.15
18	0.176	0.0299	0.14	6.15	5.40	6.25
20	0.180	0.0298	0.14	5.95	5.75	5.95
22	0.178	0.0298	0.14	5.15	4.25	4.90
24	0.172	0.0297	0.15	5.80	5.15	5.48
26	0.175	0.0298	0.13	5.35	4.75	5.75
28	0.178	0.0299	0.14	5.55	5.05	5.80
30	0.181	0.0298	0.14	5.65	4.85	6.05
32	0.178	0.0298	0.14	5.75	5.00	6.50
34	0.176	0.0299	0.14	5.50	5.05	5.75
36	0.178	0.0299	0.14	6.15	5.45	6.40
38	0.172	0.0297	0.15	5.70	5.00	6.00
40	0.176	0.0299	0.14	5.45	4.85	5.05
42	0.186	0.0298	0.13	4.65	5.40	5.30
44	0.180	0.0298	0.14	6.55	5.75	6.40
46	0.175	0.0298	0.13	6.25	6.05	6.15
50	0.178	0.0299	0.14	5.00	5.80	5.60

CHAPTER - IV

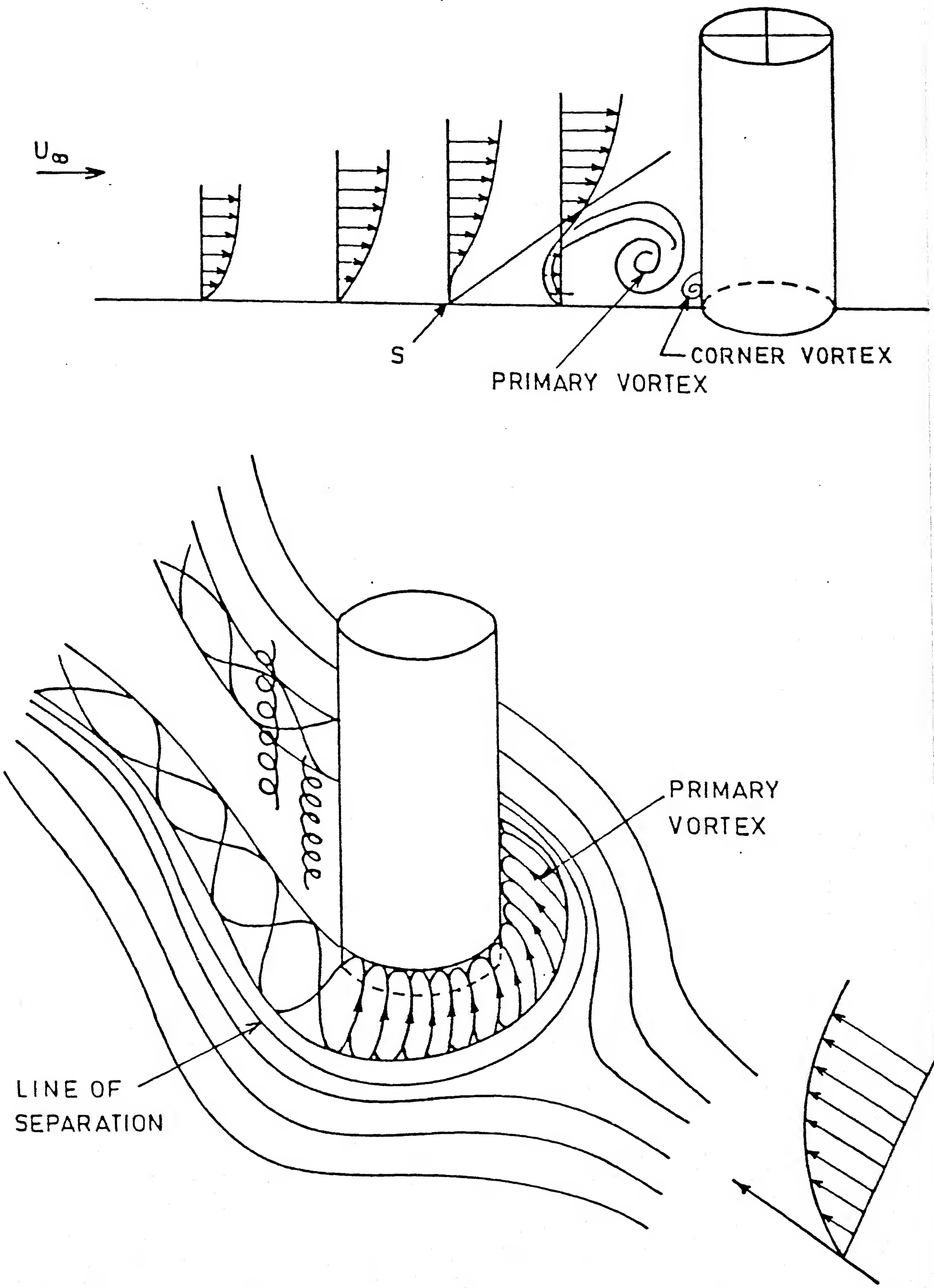
ANALYSIS AND DISCUSSION OF RESULTS

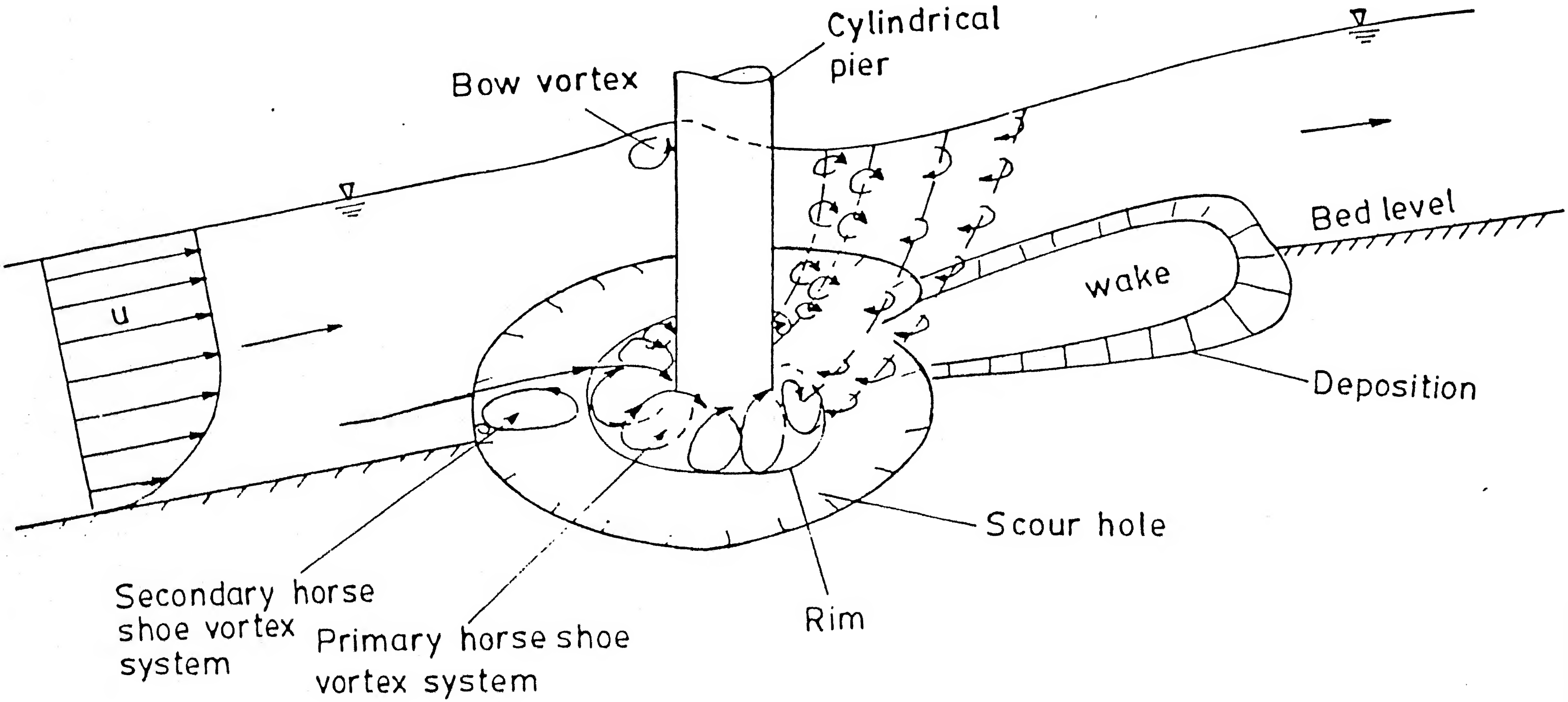
Interference effects of piers placed one closed to other are analysed for different arrangement patterns. There are three arrangement patterns viz. tandem arrangement, equilateral triangular arrangement and staggered arrangement. In the staggered arrangement, two patterns of pier positioning are considered. The data of all the experiments are analysed with respect to their interference effect.

Interference effect of piers is defined as the ratio of difference in scour depth value to the scour depth value of the pier causing interference. This is denoted as I.E. Positive value of interference effect I.E. marks the safer condition, where as the negative value indicates danger. This effect is discussed in detail for all the arrangement patterns in this chapter.

4.1 Flow Pattern Around an Isolated Pier

It has been recognised that the basic cause of 'local scour' is the interaction of horseshoe vortex formed at the junction of a pier with sediment bed. Figure 4.1 shows the sketch of the horseshoe vortex warping around the cylindrical pier before starting of the scour. Figure 4.2 (a) and (b) shows the scooping of sediment by horseshoe vortex during scouring process. It may be observed that during the scouring processes the size and velocity of the horseshoe vortex change as scour hole deepens. Horseshoe vortex wraps around back to the cylindrical


U_∞
S
PRIMARY VORTEX
CORNER VORTEX
PRIMARY VORTEX
LINE OF SEPARATION



PLAN VIEW

Fig: 4.2 (a)
SCOOPING OF SEDIMENT BY HORSESHOE VORTEX DURING SCOURING PROCESS

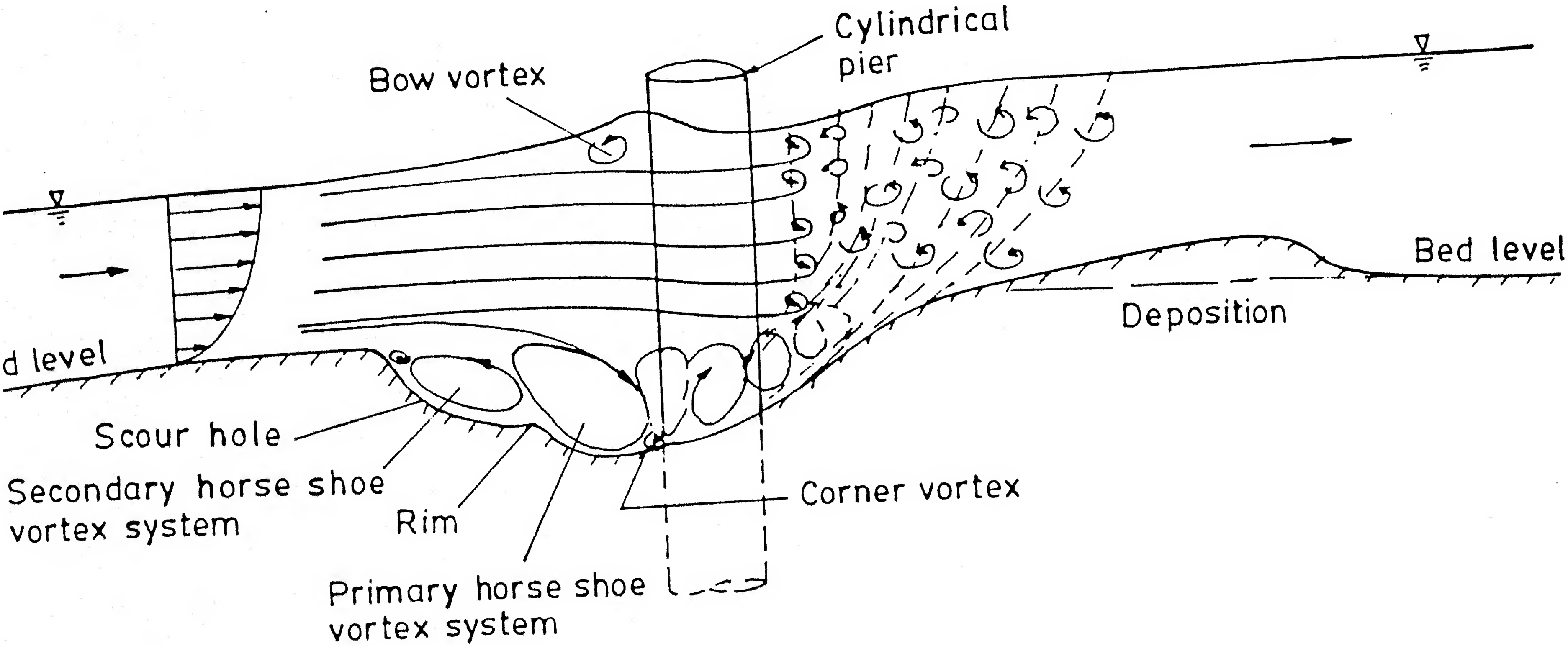


Fig: 4.2 (b)
SCOOPING OF SEDIMENT BY HORSESHOE VORTEX DURING SCOURING PROCESS (CROSS- SECTIONAL ELEVATION)

pier before and during the scouring process. When the horseshoe vortex wraps back to the cylindrical pier, it is lifted vertically, causing the shedding of vortices. These vortices move downstream with in the wake created by the flow past a cylindrical pier. This wake grows in size in downstream direction. This can be observed in the wet paint impressions of flow around cylindrical pier mounted on a flat plate as shown in Figures 4.3(a) and (b). Figure 4.3(a) is photo of the wet paint impression of flow around cylinder mounted on a rigid plate. Figure 4.3(b) shows the growth of wake behind a cylinder . Visible flow patterns are, separation zone, streak lines in the separation zone and in the near wake zone.

The flow velocity in the wake gradually develops by recovering its velocity defect. Near to the edge of wake, shed vortices line up as series one behind the other like light poles on either side of a straight road . When piers are located one behind the other, the upstream wake interferes with flow structure causing the horseshoe vortex of downstream pier. The intensity of interference depends upon the position of the downstream location. If the downstream pier is located in the centre of the wake, where the magnitude of flow will be less, the weaker horseshoe vortex will be caused. If the pier is located at the line of vortex shedding, it may be expected that horseshoe vortex strength may increase or decrease depending on the type of flow interaction and interference. When the pier is located outside the wake, it may be expected that the horseshoe vortex strength may be same as that at upstream pier or more.

4.2 Sediment Bed Patterns Behind a Single Pier

The interaction of flow patterns on erodible bed in the form of erosion and deposition indicates the magnitude of flow velocities. This is studied further by conducting experiments on single pier for long period(100hrs) and measuring the sediment erosion and deposition around the pier and its downstream. The erosion and deposition patterns are shown in Figures 4.4(a) and (b). Figure 4.4(b) give the plan form of deposition and erosion. Figure 4.4(a) shows the cross sectional elevation along the central line of the pier in the downstream direction. From these figures it may be observed that erosion is dominating till $X/D \leq 4$. The deposition along the centre line occurs till $X/D \leq 13$. Beyond this value there is slight erosion occurs.

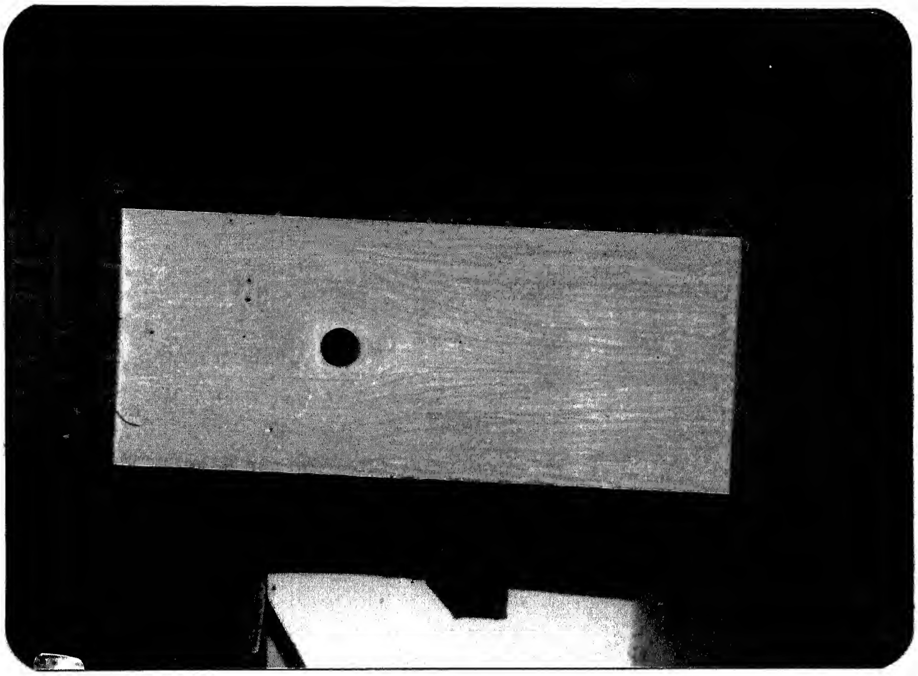
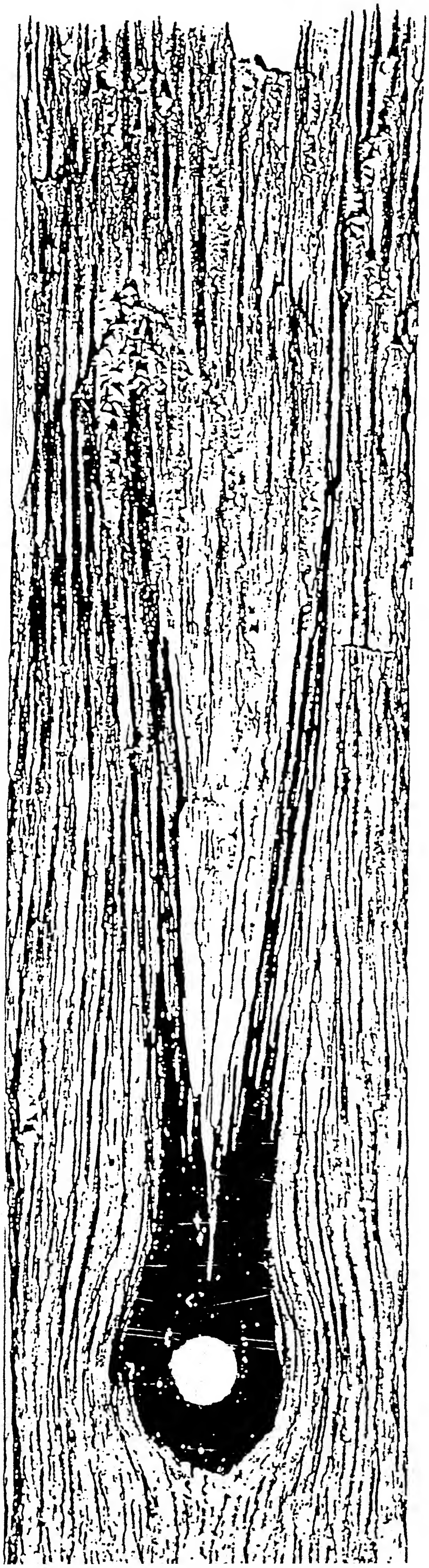


Fig: 4.3 (a)
PHOTOGRAPH OF WET IMPRESSION OF FLOW AROUND CYLINDER MOUNTED ON RIGID PLATE



Fig; 4.3 (b)
FLOW PATTERN AROUND AND BEHIND CIRCULAR CYLINDER

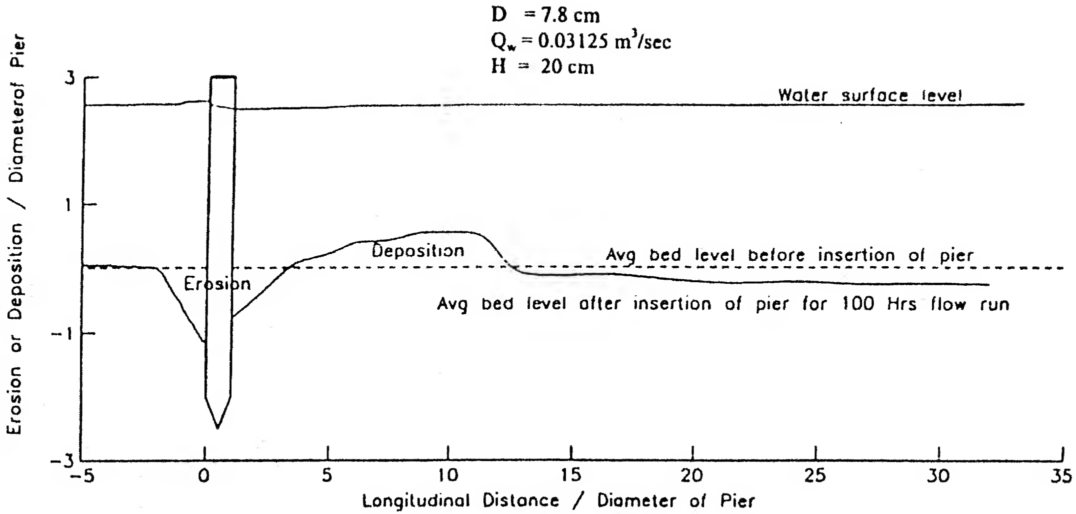


Fig: 4.4b

THE CROSS SECTIONAL VARIATION ALONG THE CENTRE LINE OF PIER ON THE WAKE ZONE SHOWING ZONE OF EROSION AND DEPOSITION OF SEDIMENT

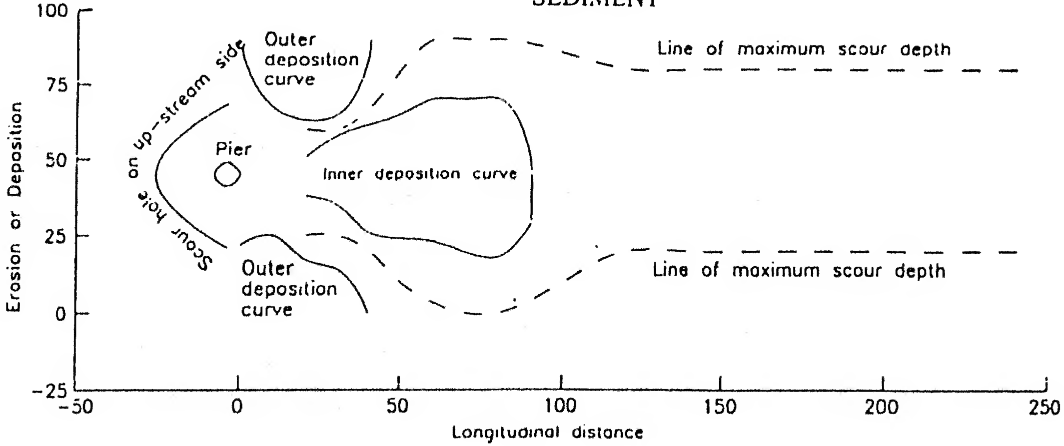


Fig: 4.4a

PLAN SHOWING THE DEVELOPMENT OF WAKE AND LINE OI MAXIMUM SCOUR DEPTH OF DOWNSTREAM PIERS

4.3 Tandem Arrangement

Definition sketch for the arrangement patterns is shown in Figure 3.1(a). The drag coefficient of circular cylinders placed in the tandem arrangement, in uniform free turbulent flow is shown in Figure 4.5(a). It may be observed that the drag coefficient of both the cylinders get altered when the clear spacing between them is less than three times the diameter. This may be due to the interference of the wake flow of the upstream pier on the downstream pier which effect downstream pier flow causing back flow type obstruction to the upstream pier. When the spacing is greater than 3D, the effect of upstream pier on the downstream pier flow pattern will be dominating and not the vice versa.

Scour depth of upstream pier (H_{su}/D) and downstream pier (H_{sd}/D) are plotted against longitudinal spacing (X/D) for flow conditions (Fr = 0.16 to 0.18) as shown in Figure 4.5(b). For two piers touching (X/D = 0), the scour depth at the front pier is same as for the single pier. With increasing separation between the piers, the front pier experiences maximum scour depth at X/D = 2.0 and thereafter decreases upto X/D = 5.0. The scour depth remains fairly constant for X/D>5.0. Here X is defined as clear spacing between two cylindrical piers arrangements.

Figure 4.5(b) also includes the variation of scour depth for downstream cylindrical pier. The magnitude of the downstream pier scour depth is always less than the upstream pier scour depth till X/D = 34.0. The reduction in scour depth is an indication of reduction in magnitude of the incoming velocity and the strength of the horseshoe vortex formed at the downstream cylindrical pier junction with sediment bed.

Similarly, with the increase in separation between the piers, at X/D = 2.0, a horseshoe vortex forms around the rear pier (its strength increases) with increase in separation. At smaller separation, vortices shed from front pier and pass close enough to rear pier to aid scouring process. Scour depth at rear pier thus increases with separation. At X/D = 4.0, the scour depth of rear pier reaches maximum. Then, it gradually decreases till X/D = 8.0. For larger separation at (X/D >8), the shed vortices pass farther from the pier and therefore are less effective in scouring process

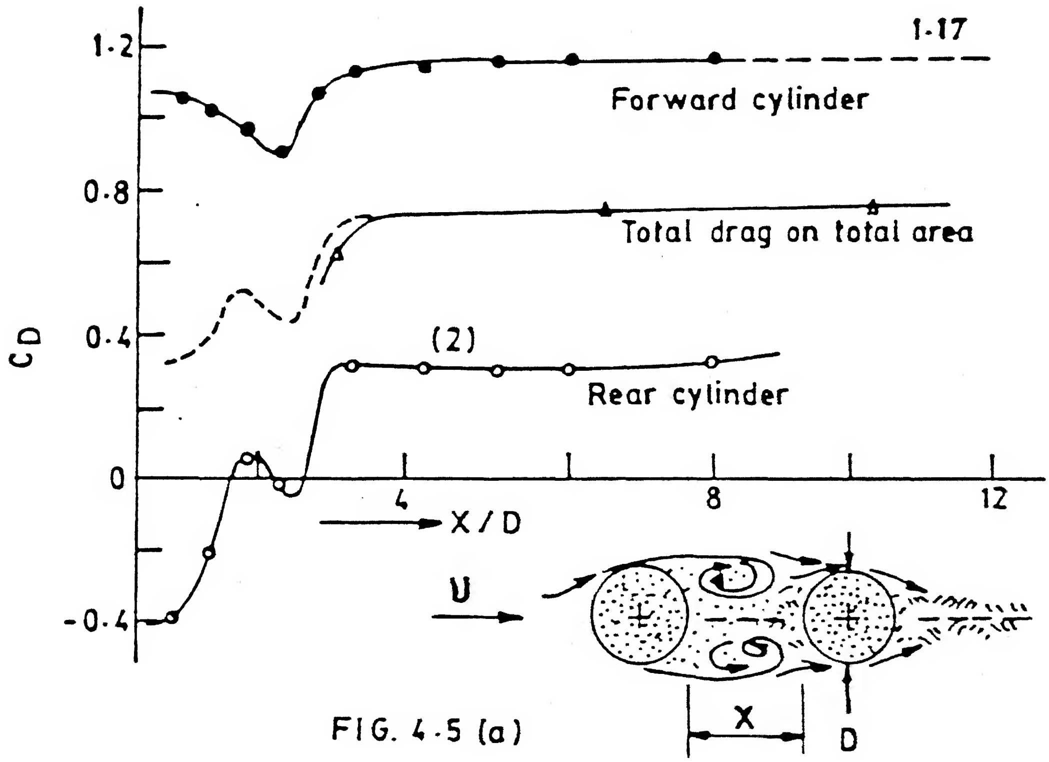


FIG. 4.5 (a)

Drag coefficients of two circular cylinders one placed behind the other (Tandem Arrangement)

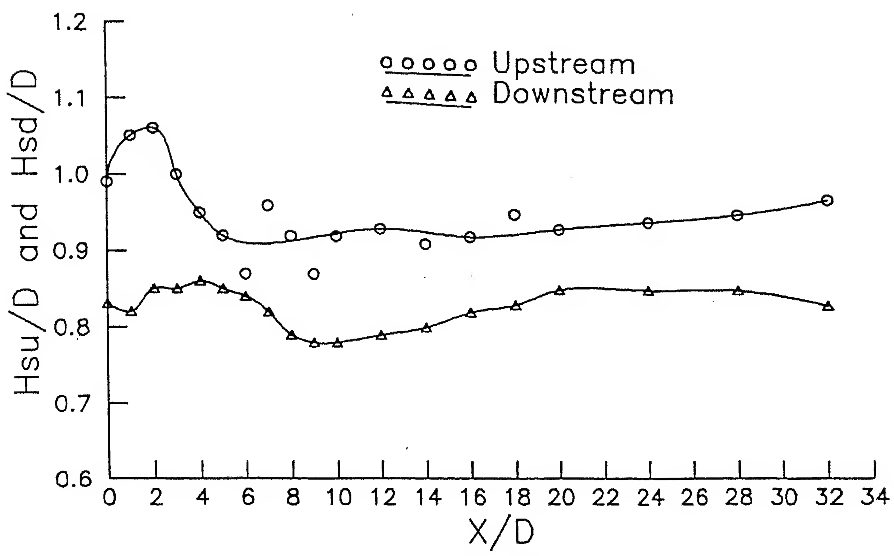


Fig: 4.5b
VARIATION OF MAXIMUM SCOUR DEPTH OF DOWNSTREAM WITH RESPECT TO UPSTREAM WHEN THE CYLINDERS ARE PLACED LONGITUDINALLY

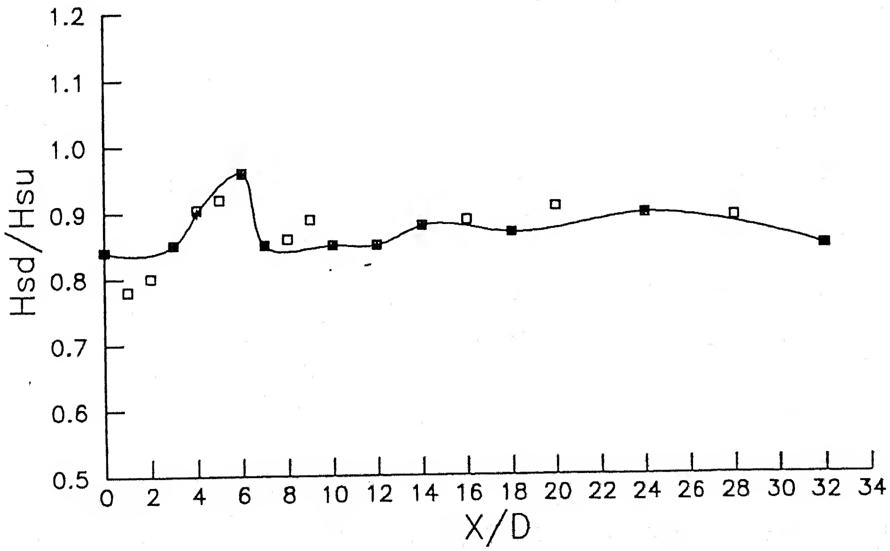


Fig: 4.5c
VARIATION OF MAXIMUM SCOUR DEPTH OF UPSTREAM AND DOWNSTREAM WHEN THE CYLINDERS ARE PLACED LONGITUDINALLY

In addition, the bed level between the scour holes builds up. At this stage, both the upstream pier and downstream pier act individually. This observation can be seen in Figures 4.5(b) and (c).

The maximum scour depth(H_{sd}) at downstream pier is non-dimensionalised with maximum scour depth(H_{su}) of upstream pier i.e., H_{sd}/H_{su} is plotted against X/D for Fr = 0.16 to 0.18 as shown in Figure 4.5(c). The following characteristics are observed. In the initial stages, the scour goes on increasing from X/D = 0 to X/D = 6. The scour depth reaches maximum at X/D = 6, then it decreases at X/D = 7. At X/D > 7, the scour depth remains constant.

4.3.1 Interference Effect for Tandem Arrangement

Interference effect for tandem arrangement is defined as

$$\text{Interference Effect (I.E.)} = (H_{su} - H_{sd})/(H_{su}).$$

Here the flow past the upstream pier is considered to be interfering on the flow characteristics of the downstream pier. The interference of flow characteristics, like change in the magnitude of approach velocity, and change in the flow structure particularly at the edge of the wake of the upstream pier are considered to affect the magnitude of scour depth of the pier getting interference. Here the downstream pier gets the interference of upstream pier. The magnitude of I.E computed as per the definition stated above is plotted in Figure 4.5(d). The magnitude of I.E is always positive indicating the reduction in the scour depth of downstream pier with respect to upstream. Fluctuations in the I.E value particularly when piers are closely spaced is (X/D < 10) are dominating. The first reduction in I.E value occurs at X/D = 3.0. In this zone, the scour depth of upstream piers gets affected due to presence of down stream pier. Downstream pier causes a suction effect on upstream scour depth, thus causing the bed level between them always below the general bed level. This effect occurs as long as the downstream pier is positioned within the near wake zone of the upstream pier. As the spacing increases the second fluctuation occurred between 4 < X/D < 10. In this zone, the far wake is in the developing state. Due to this developing state of far wake the fluctuations are present. For X/D > 10, the fluctuations in I.E values dampens and slowly the zero interference effect is reached when X/D > 24.

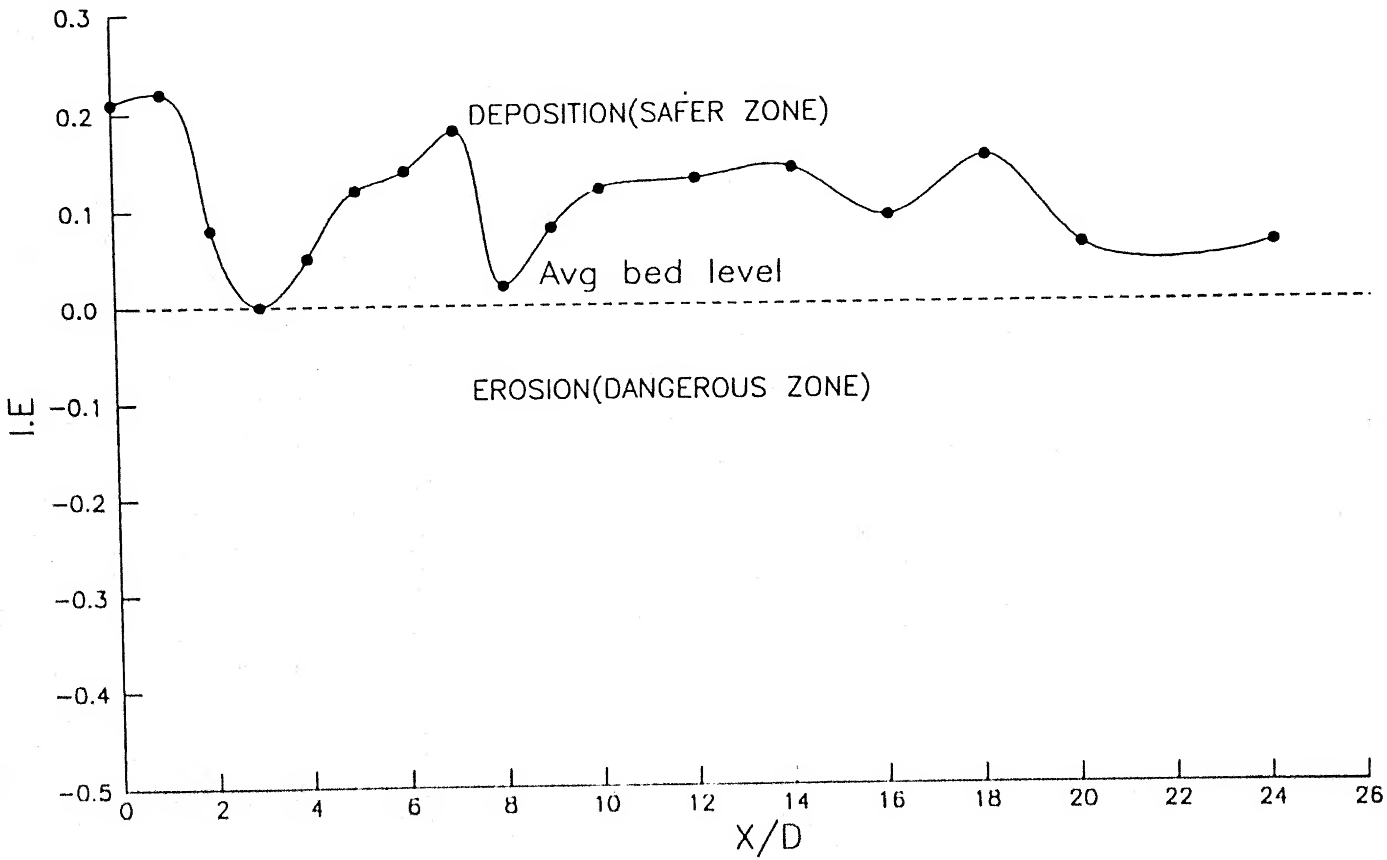


Fig: 4.5d
INTERFERENCE EFFECT OF UPSTREAM PIER ON DOWNSTREAM PIER IN TANDEM ARRANGEMENT

4.4 Equilateral Triangular Arrangement

The arrangement pattern is shown in the definition sketch Figure 3.1(b) (pattern III). Details of data are shown in the table 3.2. The scour depth of the upstream pier (Hs u/s(maximum)/D) is plotted against spacing between the piers (S/D) for the flow conditions Fr = 0.17 to 0.18 as shown in Figure 4.6(a). In the initial stages, the scour depth increase from S/D = 0 to S/D = 1.0. The scour reaches maximum at S/D = 1.0, then it decrease at S/D = 3.0. When S/D > 5.0, the scour depth remains constant, here the piers acts individually or in other words one can say that interference effects are dominant till S/D < 5.0.

In the second case, the scour depth of the downstream pier (left and right) is plotted against spacing between the piers (S/D) for the flow conditions Fr = 0.17 to 0.18. From Figure 4.6(b), it is observed that both the downstream (left and right) i.e., Hsl(maximum/D) and Hsr(maximum)/D behaves in the similar pattern. It is found that the scour depth, in the initial stages increase from S/D = 0 to S/D = 1.0. The scour reaches maximum at S/D = 1.0, then it decreases upto S/D = 3.0 and thereafter increases upto S/D = 4.0 when S/D > 4.0, the scour depth remains constant. The scour depth on the downstream pier is more than that of upstream pier.

4.4.1 Bed Level Variations Between Upstream Pier and Downstream Piers

Scour depth of both upstream pier and downstream piers are increasing when the piers spaced X/D≤ 3.0 in equilateral triangular arrangement, where "X" is the distance measured from upstream cylinder towards the downstream cylinder along the line joining their centres. The increase in magnitude of scour depth at upstream pier is slightly more than that at downstream pier. This indicates the mutual interference of flow on the horseshoe vortex formed on both cylindrical piers. This interference effects aids in scouring more, when S/D<3.0. When S/D>4.0, upstream pier acts as an isolated pier where as downstream pier still have interference of upstream pier resulting in less scour depth.

The bed level variations between upstream pier and downstream piers(left and right) are drawn as shown in Figure 4.6(c). The magnitude of maximum erosion occurs at or near the piers. In between the piers erosion or deposition with respect to original bed level occurs as

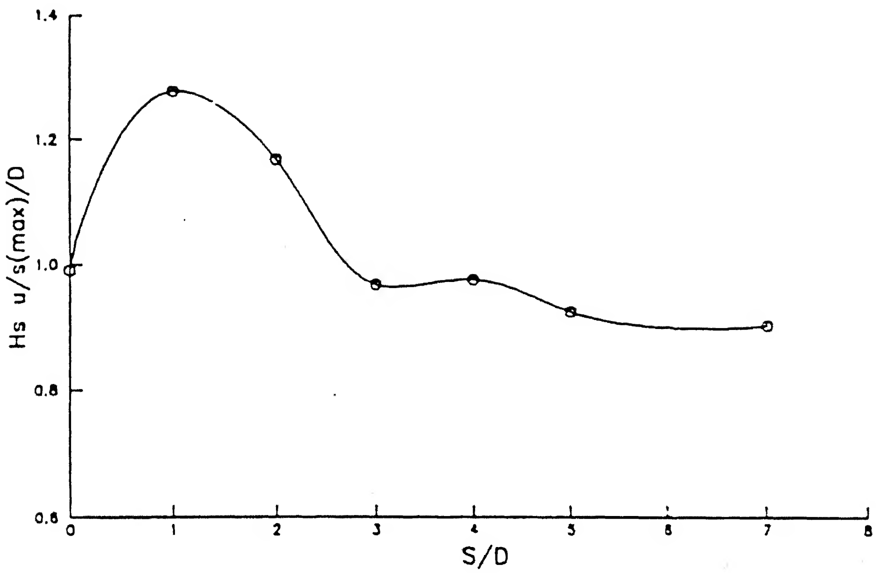


Fig: 4.6a

SCOUR DEPTH VARIATION OF UPSTREAM PIER FOR DIFFERENT LOCATIONS OF DOWNSTREAM PIERS IN EQUILATERAL TRIANGULAR PATTERN

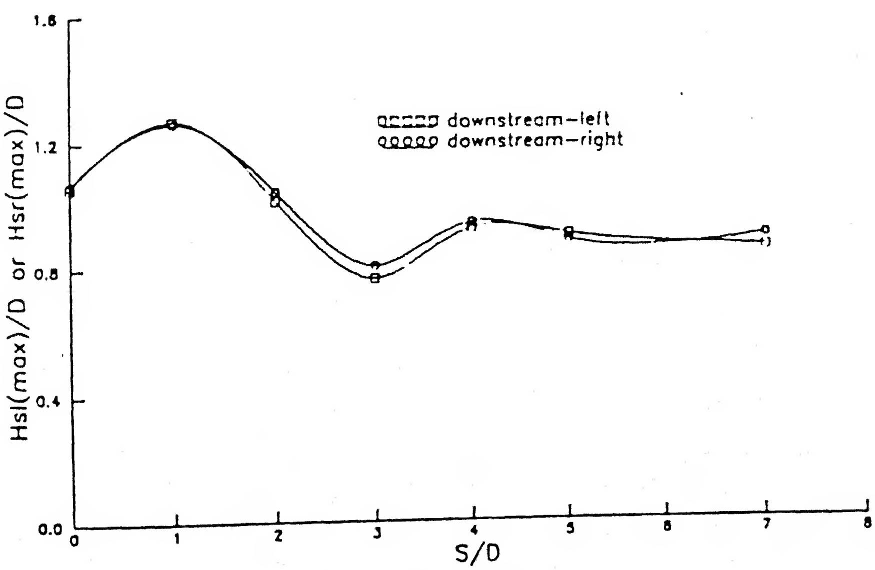


Fig: 4.6b

SCOUR DEPTH VARIATION OF DOWNSTREAM FOR DIFFERENT LOCATIONS WITH RESPECT TO UPSTREAM PIER IN EQUILATERAL TRIANGULAR PATTERN

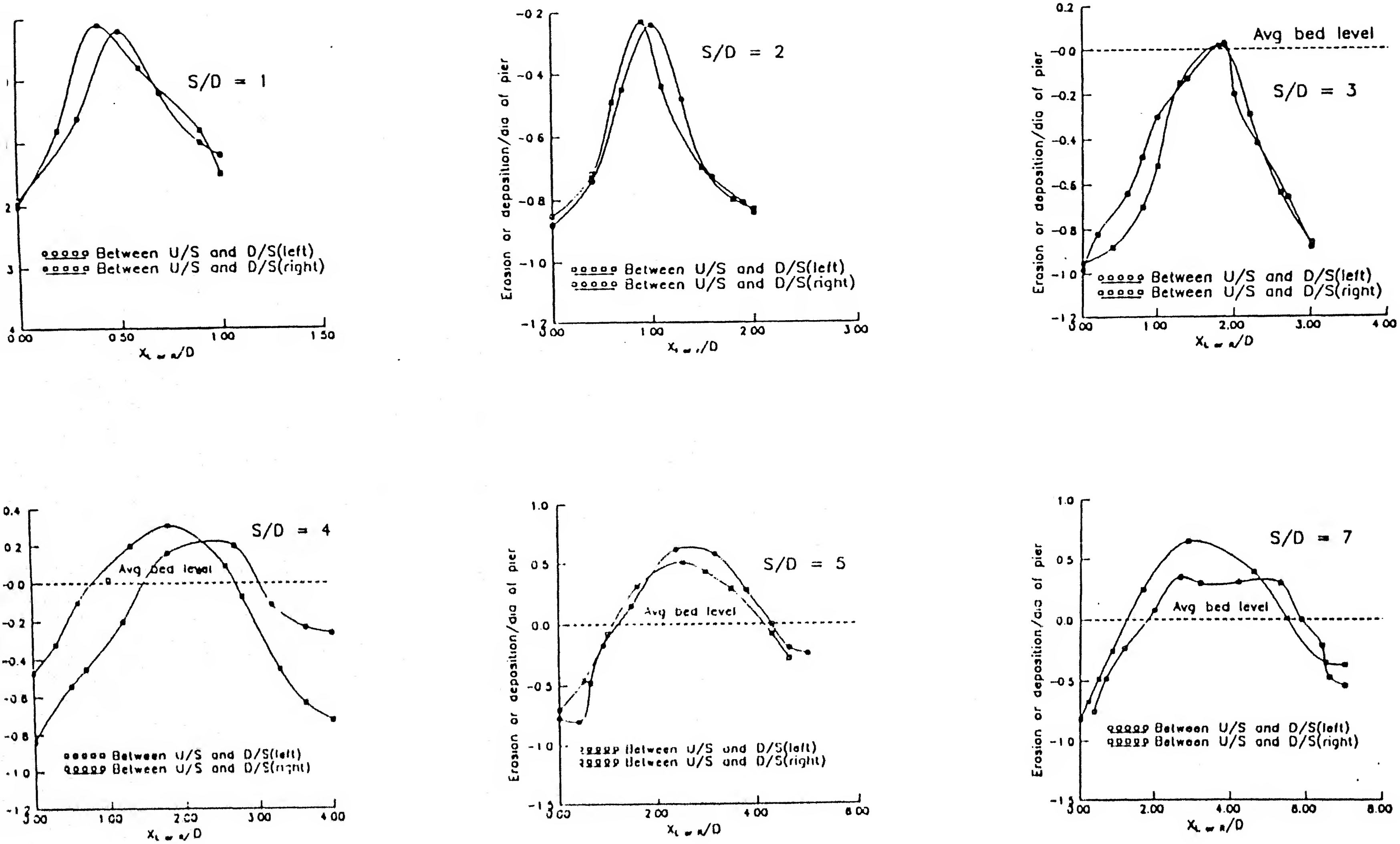


Fig: 4.6c
EROSION AND DEPOSITION OF SEDIMENT BED PROFILES BETWEEN UPSTREAM AND DOWNSTREAM (LEFT & RIGHT PIERS FOR DIFFERENT SPACING)

the spacing S/D increases. The erosion is dominating when S/D<3.0 and deposition dominates when S/D>3.0. The magnitude of erosion of the bed level is maximum for S/D = 1.0, and it is of the order of 0.9D. As spacing increases reduction in erosion occurs and reaches general bed level at S/D = 3.0. Erosion and deposition patterns between the piers indicates the interference effect of one with the other pier. Region in which erosion is more, downstream pier horseshoe vortex may be aided by upstream pier vortex shedding. In the region of deposition, the horseshoe vortex strength of downstream pier may be reduced due to the wake of upstream pier. It may be observed further that for spacing of piers, S/D≤ 3.0, they lie in the zone of near wake of the upstream pier.

4.4.2 Interference Effect For Equilateral Triangular Arrangement with Respect to Upstream Pier

The interference effect I.E is computed between the upstream pier and the downstream left pier, as well as between upstream pier and downstream right pier separately. The magnitude of I.E is plotted for different equilateral length as spacing between the piers as shown in Figure 4.6(d). It may be observed that the magnitude of I.E is positive except for very close spacing, i.e. less than D. However, it may be seen that maximum positive value occurs when S/D = 3.0. With increase in S/D, I.E value decreases, After S/D > 4.0, the magnitude of I.E is almost constant nearing to zero value.

4.4.3 Interference Effect for Equilateral Triangular Arrangement Pattern with Respect to Isolated Pier Scour Depth

The magnitude of upstream pier scour depth at S/D = 5.0 and 7.0 of Figure 4.6(e) can be considered as the magnitude of scour depth of an isolated pier. This is because the downstream piers are not effecting upstream flow conditions. Defining interference effect of a pier with respect to isolated pier as

I.E* = (scour depth of isolated pier - scour of pier under consideration)/(scour of isolated pier)

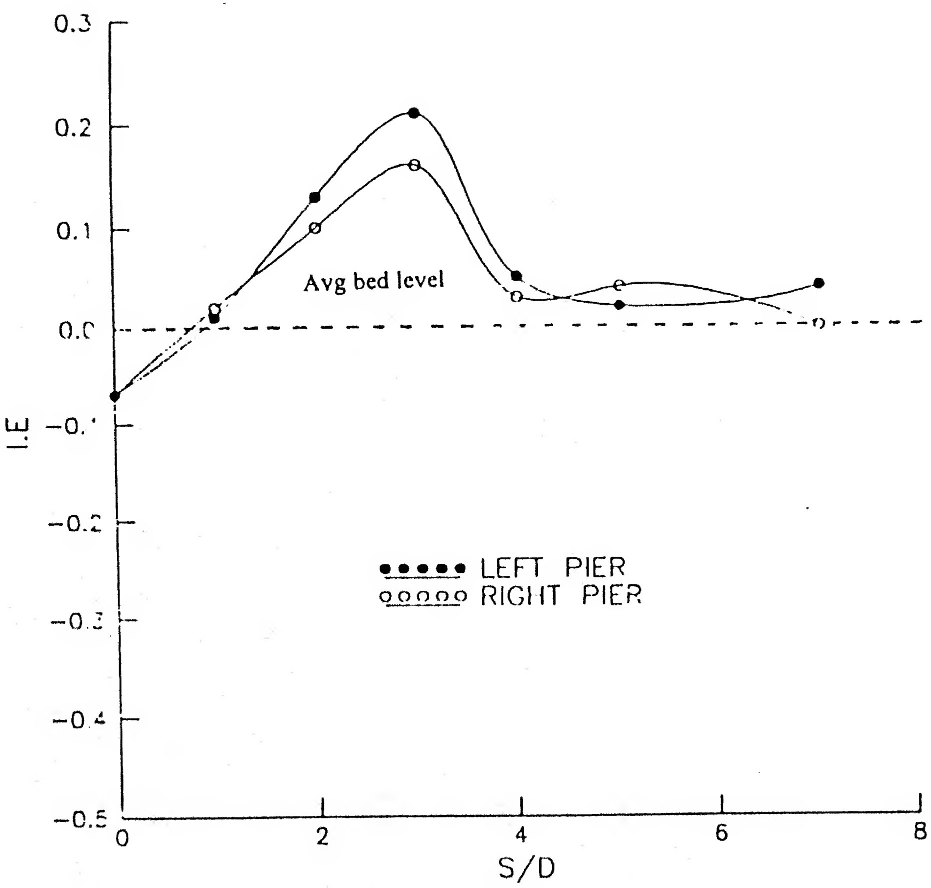


Fig: 4.6d

INTERFERENCE EFFECT OF DOWNSTREAM WITH RESPECT TO UPSTREAM PIER IN EQUILATERAL TRIANGULAR ARRANGEMENT PATTERN

Interference effect of upstream pier with respect to isolated pier is denoted as I.E*us corresponding to downstream piers located at left and right positions as $I.E_{DSL}$ and $I.E_{DSR}$. The interference effects of all three piers in equilateral triangular arrangement with respect to isolated pier scour depth is shown in Figures 4.6(e) to 4.6(g). Interference effects of upstream, downstream(left) and downstream(right) are shown in Figures 4.6(e), (f) and (g) respectively. The magnitude of negative value of interference effect is of the order of 0.4 and it is same for all the three piers. The position of maximum (-)ve I.E occurs at S/D = 1.0. The zone of negative I.E for upstream pier is of the order of S/D<5 and for downstream piers less than 2.2. The magnitude of highest positive I.E occurs for downstream piers at S/D = 3.0 and its magnitude is of the order of 0.2. For spacing greater than 4D, for all the three piers, the effect of interference is almost zero. This indicates clearly that when the spacing of piers in equilateral triangular arrangement is greater than 4D, the piers acts almost independently.

4.5 Staggered Arrangement Pattern - I

The staggered arrangement pattern-I is shown in Figure 3.1(c). This arrangement pattern may be encountered, when the span of the bridge is long and lateral interference of piers is very less. In such situation, This study is applicable if a pier of downstream bridge comes under the influence of wake of upstream pier.

Experiments on the scour depth of upstream and downstream piers were carried out for the flow conditions having Fr = 0.17 to 0.19 in flume A. The arrangement pattern consists of locating upstream pier at 3.3m from inlet in the centre of the flume and varying the positions of downstream piers longitudinally and laterally. Longitudinal spacing of downstream piers were kept as 5D, 10D, 15D, 20D, 25D and 30D. The lateral spacing of piers at a given longitudinal location varied with clear spacing Z/D = 1 to 8 in the steps of one. Here "X" is longitudinal clear spacing measured from the upstream pier to the downstream pier location and "Z" is lateral clear spacing between the downstream piers. Figures 4.7(a) to 4.7(f) shows the variation of scour depth of upstream pier, when the spacing of the downstream piers was varied. Figures 4.8(a) to 4.8(f) shows the variation of scour depths of downstream piers(both left and right)with Z/D values at different X/D locations.

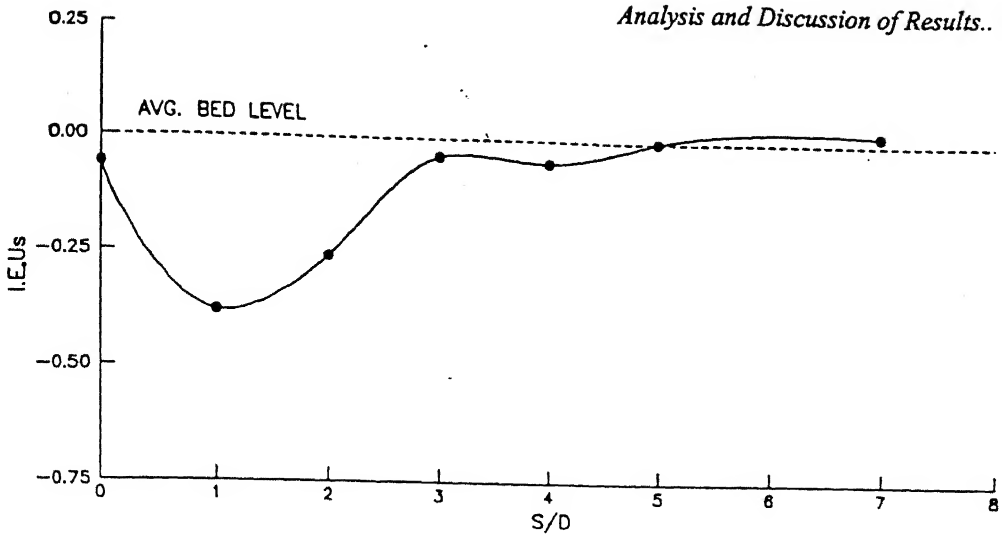


Fig: 4.6e
INTERFERENCE EFFECTS OF UPSTREAM PIER WITH RESPECT TO ISOLATED PIER

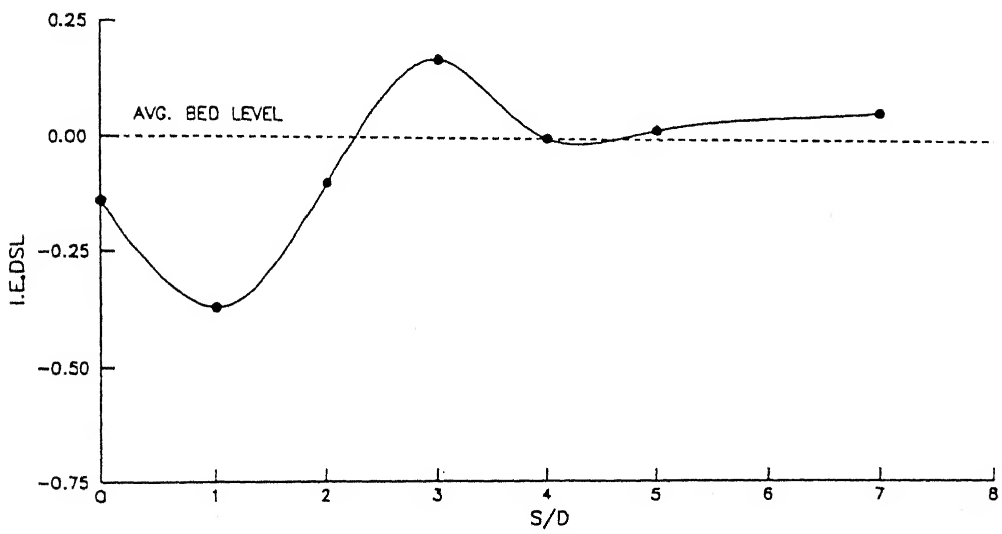


Fig: 4.6f
INTERFERENCE EFFECTS OF DOWNSTREAM PIER (LEFT) WITH RESPECT TO ISOLATED PIER

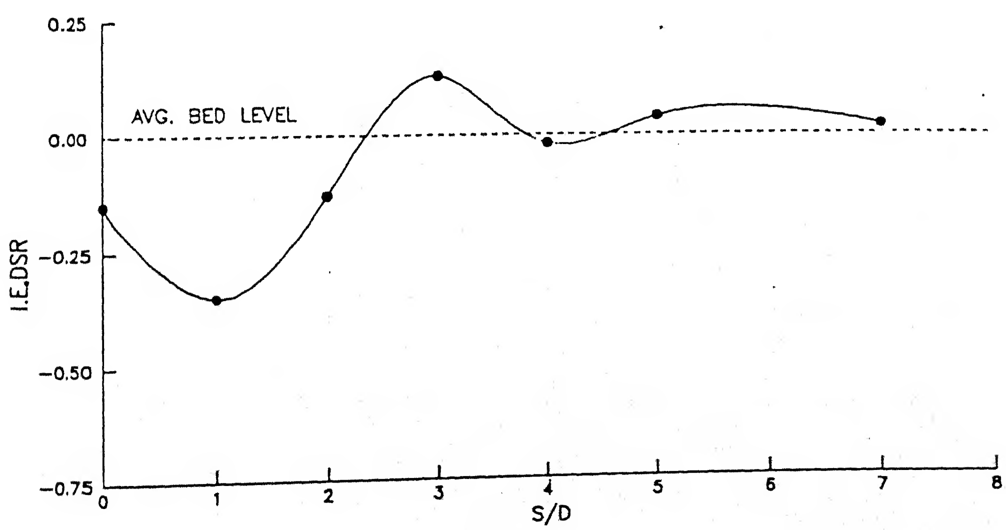


Fig: 4.6g
INTERFERENCE EFFECTS OF DOWNSTREAM PIER (RIGHT) WITH RESPECT TO ISOLATED PIER

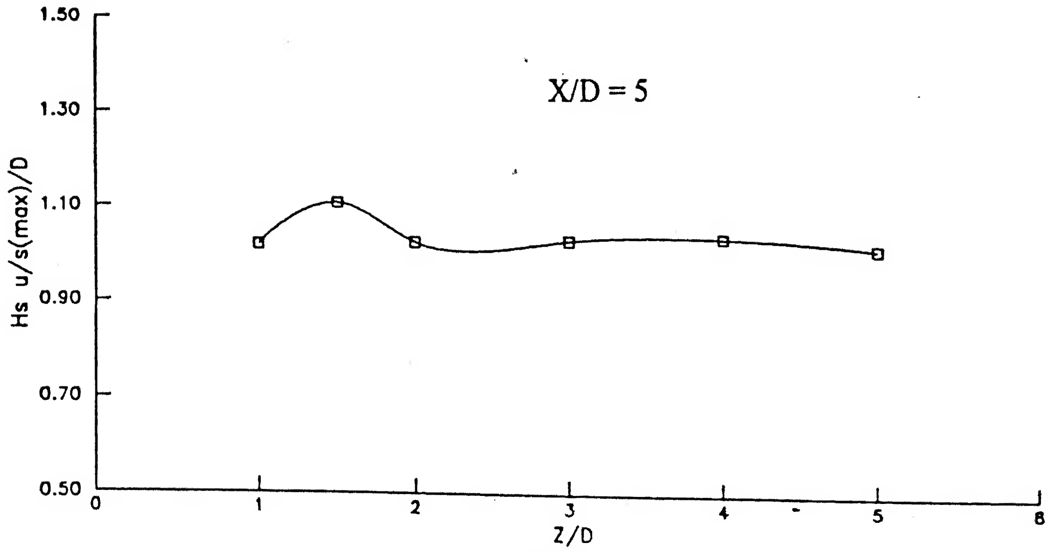


Fig: 4.7a

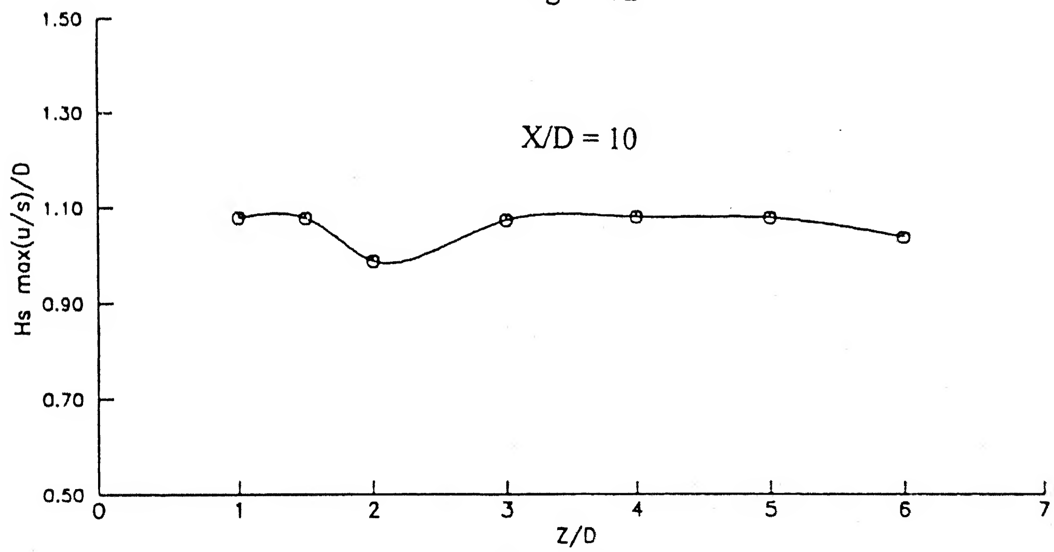


Fig: 4.7b

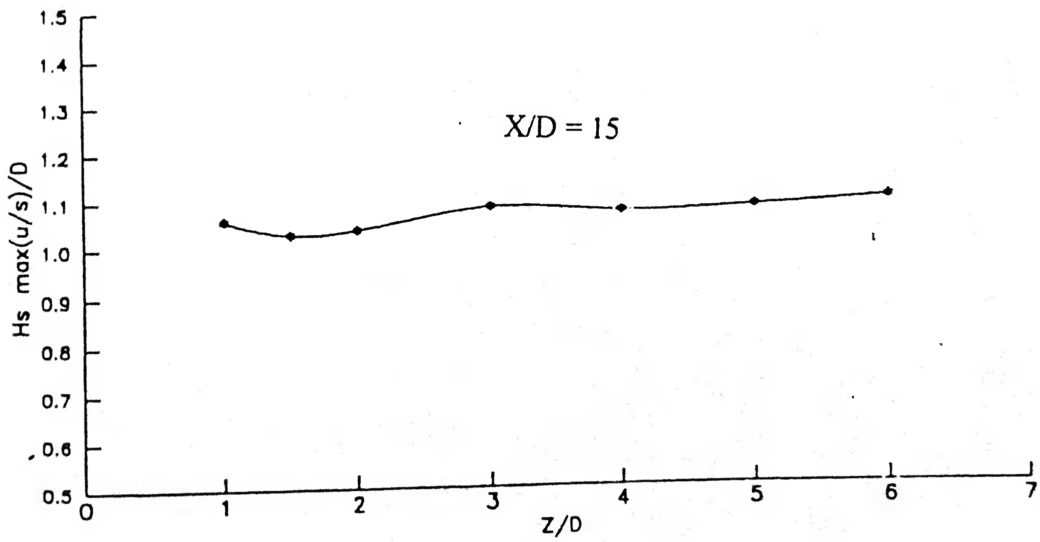


Fig: 4.7c

VARIATION OF MAXIMUM SCOUR DEPTH ON UPSTREAM SIDE

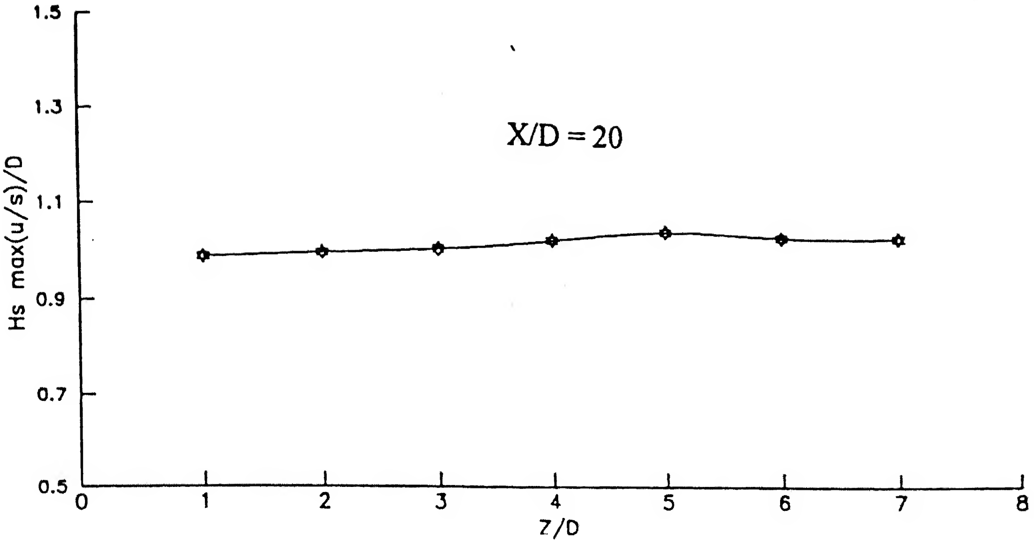


Fig: 4.7d

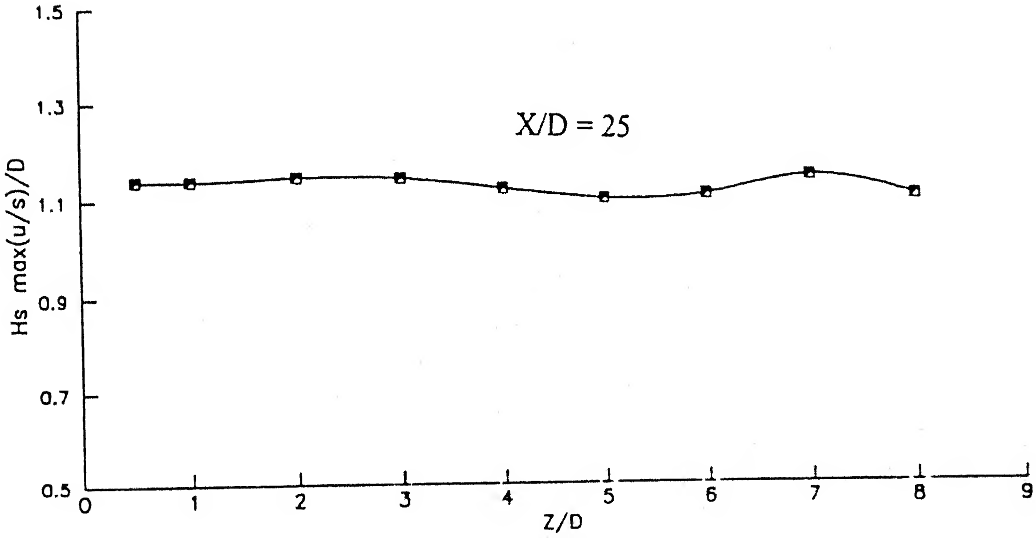


Fig: 4.7e

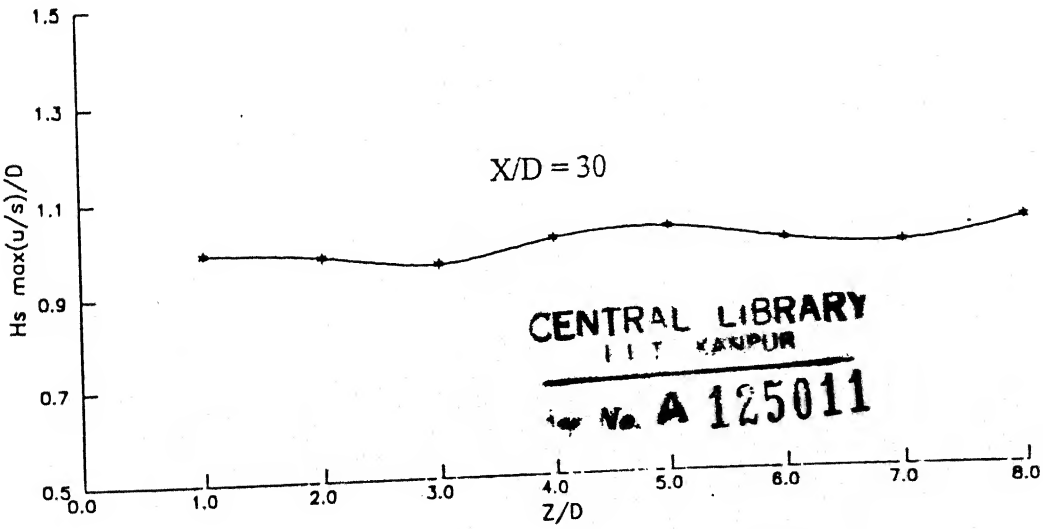


Fig:4.7f

VARIATION OF MAXIMUM SCOUR DEPTH ON UPSTREAM SIDE

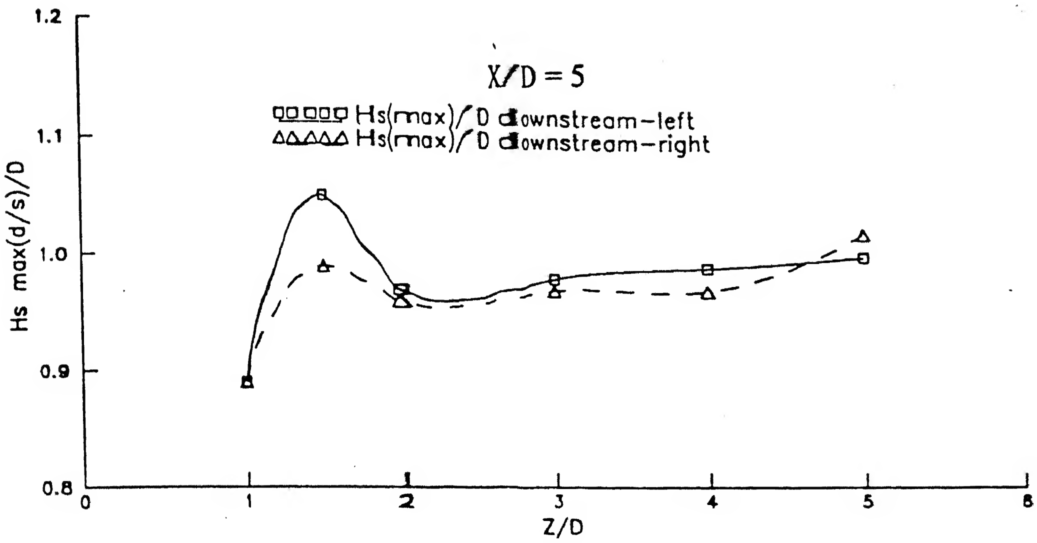


Fig: 4.8a

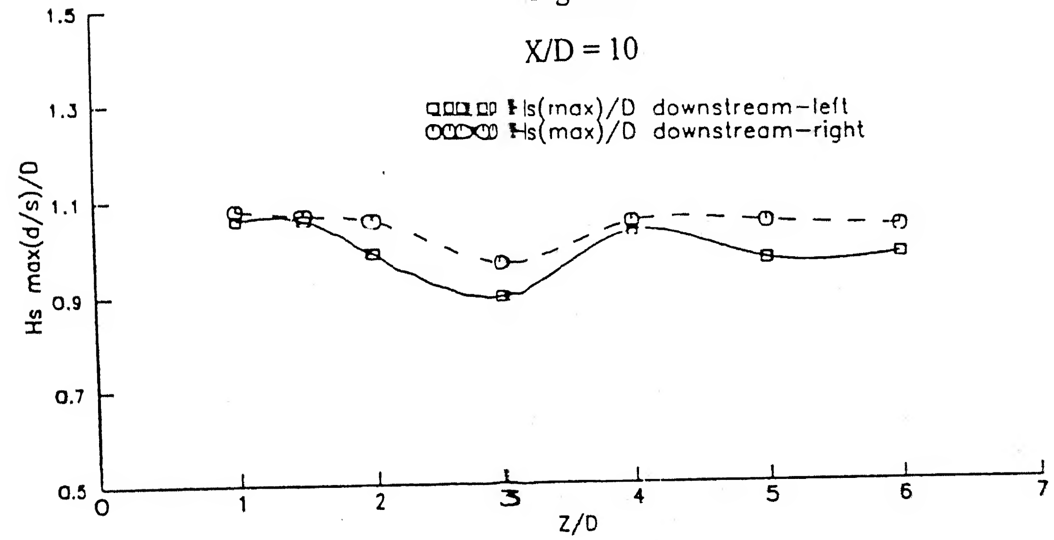


Fig: 4.8b

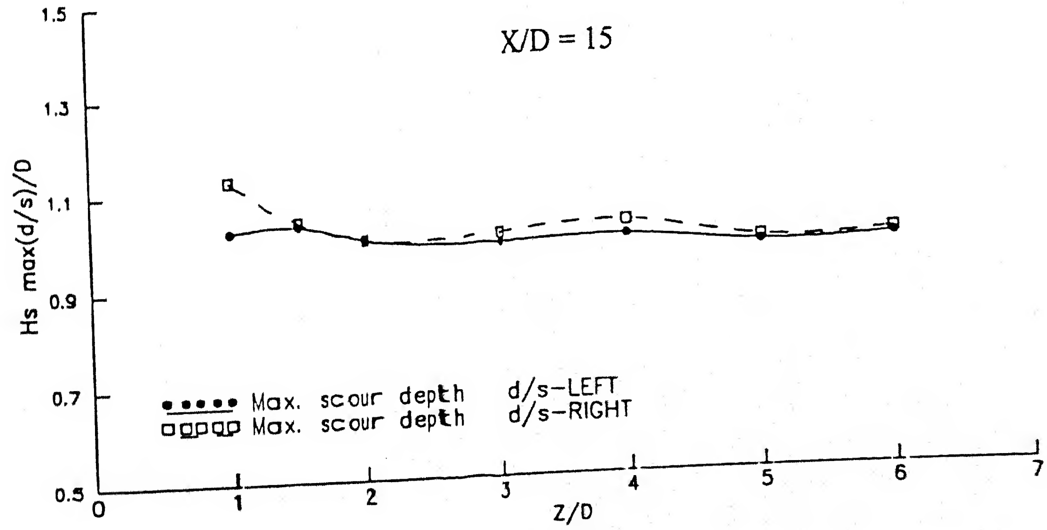


Fig:4.8c

VARIATION OF MAXIMUM SCOUR DEPTH ON DOWNSTREAM SIDE

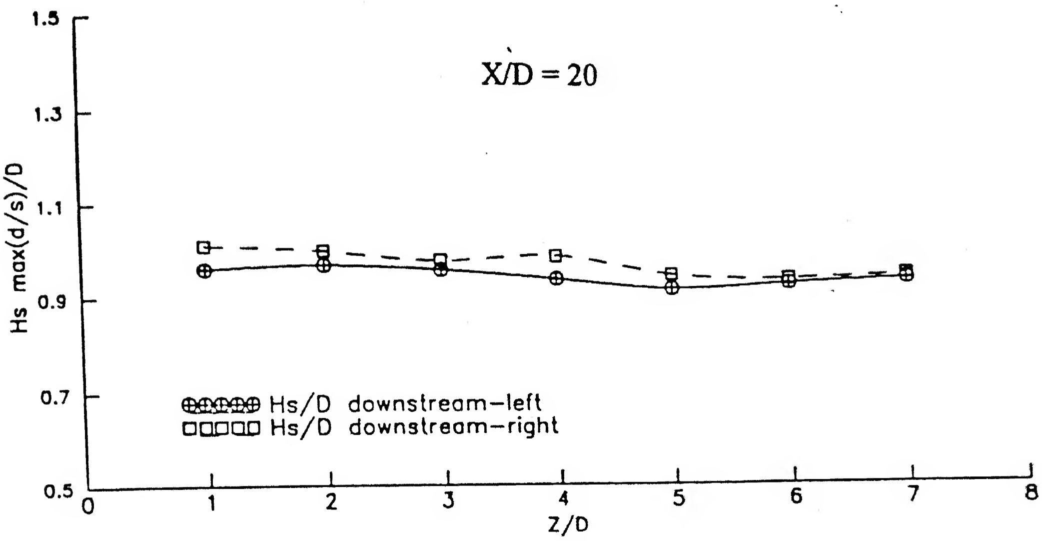


Fig: 4.8d

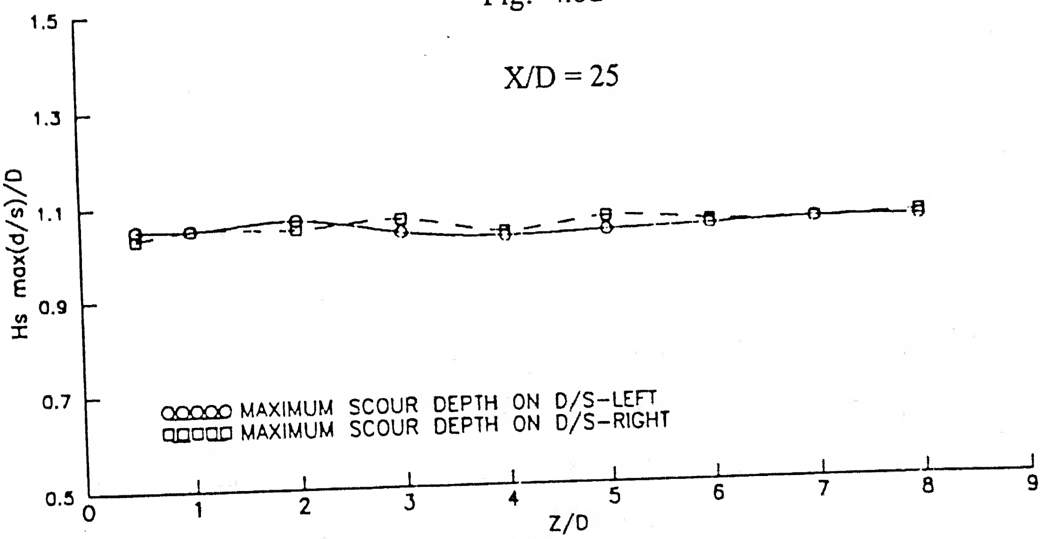


Fig: 4.8e

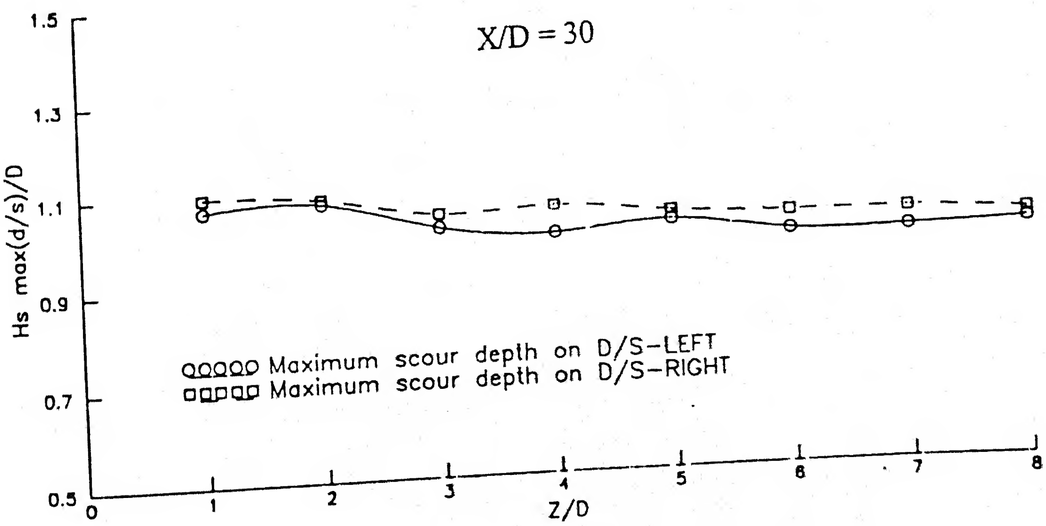


Fig:4.8f

VARIATION OF MAXIMUM SCOUR DEPTH ON DOWNSTREAM SIDE

The maximum scour depth at upstream pier increases from 0.99D to 1.14D. For X/D = 5 the magnitude of maximum scour depth reaches 1.14D and then decreases till 1.0D. Thereafter it remains almost constant. When X/D = 10, the scour depth decreases from Z/D = 1 to Z/D = 1.5, then it again decreases from Z/D = 2.0. to Z/D ≥ 3, and there after, the scour depth remains constant. At X/D = 15, 20, 25 and 30, the upstream scour depth remains constant. This can be observed from Figures 4.7(a) to 4.7(f).

The maximum scour depth at downstream pier Hs/D(d/s) i.e., Hs maximum(d/s)/D (left and right) is plotted against Z/D as shown in Figure 4.8(a). It may be observed that when X/D = 5, the scour depth gradually increases from Z/D = 1.0 to Z/D = 1.5, it reaches maximum scour depth at Z/D = 1.5. Then, it decrease till Z/D = 2. When Z/D > 2, the scour depth remains constant, this indicates that the effects of flow dominates in the zone of Z/D<2

In Figure 4.8(b), when X/D = 10, the scour depth decreases from Z/D = 1.5 to Z/D = 3 and it reaches minimum at Z/D = 3.0. Again, it increases at Z/D = 4 and decreases at Z/D = 5.0.Thereafter,when Z/D>5,scour depth remains constant. Here interference effects of flow are valid till Z/D < 5 .

In Figure 4.8(c), when X/D = 15, Z/D = 1.0, the scour depth reaches maximum .It decreases upto Z/D = 2.0, thereafter the scour depth remains constant. In all the cases both downstream(left and right) behaves in the similar pattern.

In the Figure 4.8(d), when X/D = 20, the scour depth reaches maximum at Z/D = 2.0 and Z/D = 1.0 for downstream(left and right) respectively. The interference effects of flow is visible for downstream(left and right) at Z/D<5.0. Thereafter, the piers acts individually.

In Figure 4.8(e), when X/D = 25, the scour depth reaches maximum for downstream(left) at Z/D = 2.0, and downstream(right) at Z/D = 3.0.The interference effects of flow are valid for downstream(left and right) at Z/D < 6.0. Thereafter, the scour depth remains constant.

In Figure 4.8(f), when X/D = 30, the scour depth reaches maximum for downstream(left and right) at Z/D = 2.0 and Z/D = 1.0 respectively. The interference effects of flow are valid till Z/D < 5.0. Thereafter, the scour depth remains constant.

4.5.1 Interference Effect of Staggered Arrangement(Pattern - I)

The interference effect I.E for the staggered arrangement with one pier upstream and two piers downstream is shown in Figure 4.9. It may be observed that I.E takes both positive and negative values. The zone of positive value of I.E can be considered safer, because the downstream pier scour depth is less than upstream pier scour depth. The zone of negative I.E is considered dangerous because the magnitude of downstream pier scour depth is more than upstream pier scour depth. There are few zones at which negative value of I.E is observed. These are potential zones of danger. The highest magnitude I.E.(negative) will be of the order 0.1. The maximum negative of I.E occurs mostly at the zone Z/2D = 0.2 to 0.5D.This zone can be considered as the edge of the wake of upstream pier.

4.5.2 Location of Maximum Scour Depth Region in the Wake of an Isolated pier

Development of wake and the line of maximum scour depth in the wake zone. Figure 4.10 shows the growth of wake edge behind a circular cylindrical pier taken from wet paint impression study on rigid flat bed. For this diagram, the line of maximum scour depth occurred on downstream piers in staggered arrangement pattern - I is shown. This data is taken from Figures 4.8(a) to 4.8(f). It may be observed that line of maximum scour depth lies within the wake zone, but near to the edges. Spacing of these lines of maximum scour depth increases in the downstream direction. The position of vortex street taken from boundary layer theory by Schlichting at Reynolds number of cylinder as 281 is incorporated on this plan view. It may be observed that the line of vortex street coincide at line of maximum scour depth. The Reynolds number at which maximum scour depth line obtained was $1.05 * 10^5$. It may be noted that the Reynolds number of vortex sheet plotted and line of maximum scour depth differ very widely. From Figure 4.10 it may be remarked that the possibility of movement shed vortices behind a cylindrical pier, coincides on the line of maximum scour depth.

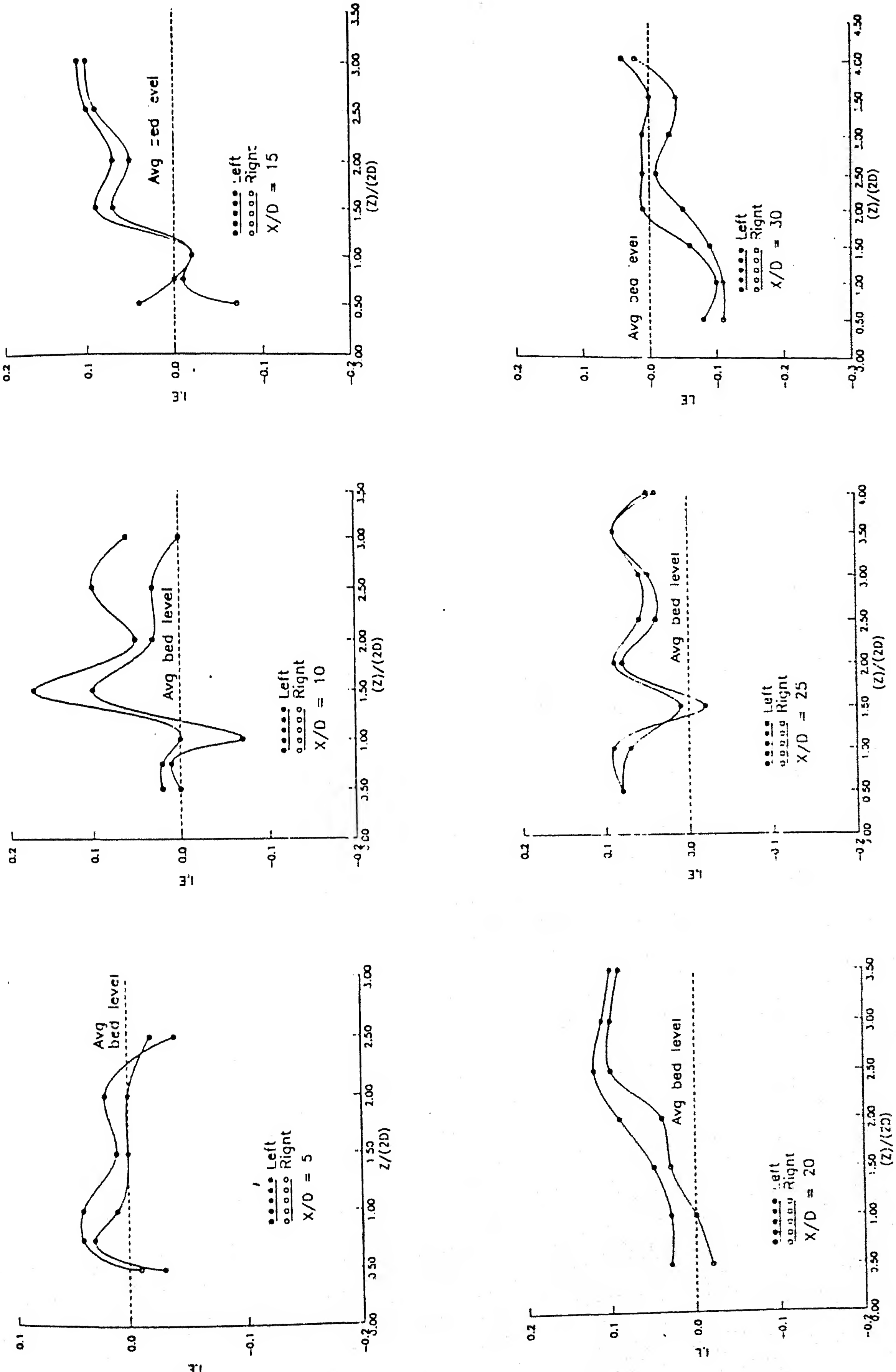


Fig: 4.9

INTERFERENCE EFFECT FOR STAGGERED ARRANGEMENT PATTERN - I

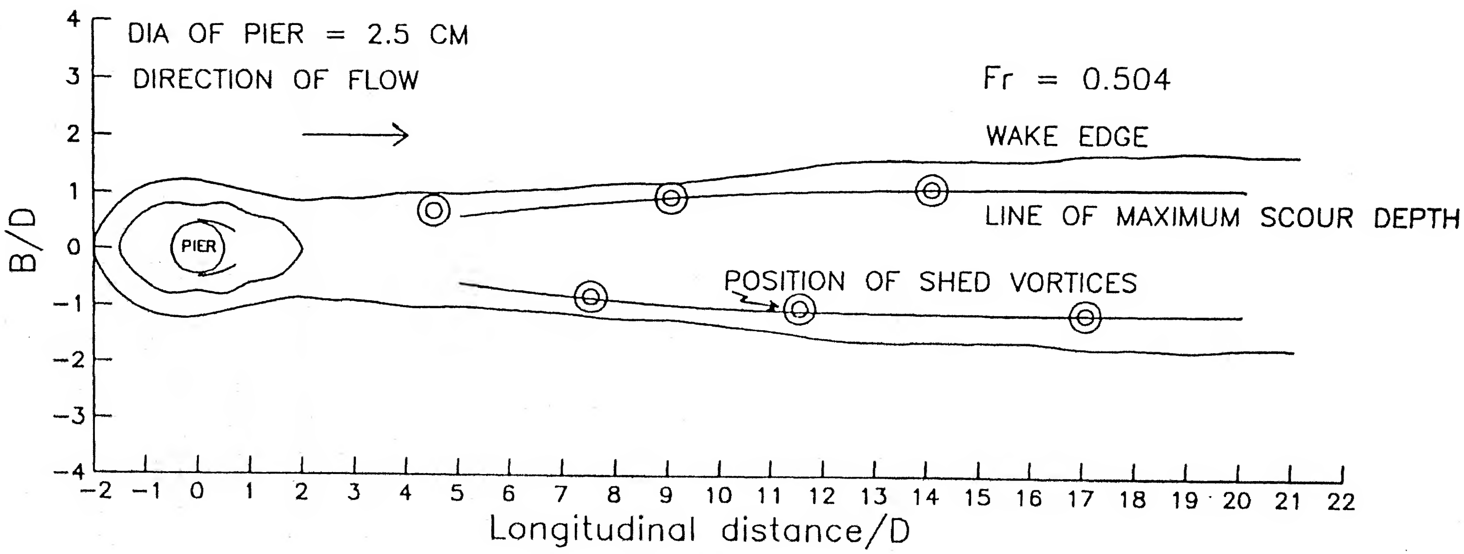


Fig: 4.10
PLAN FORM WAKE DEVELOPMENT, LINE OF MAXIMUM SCOUR DEPTH AND POSITION OF SHED VORTICES FOR STAGGERED PATTERN - I

4.6 Staggered arrangement (Pattern - II)

This arrangement pattern contains two piers upstream and only one pier downstream as shown in Figure 3.1(d). This kind of arrangement pattern may be seen in smaller span lengths of bridge piers. In this situation there is a possibility of maximum flow velocity occurring on the centre line of the spacing in the downstream direction. If a downstream bridge pier is located on this line, the possibility of higher flow velocity causing higher local scour depth around the downstream bridge pier may be expected. Experiments are focused to evaluate the zone of maximum scour depth of downstream pier incomparision to the upstream pier scour depth.

4.6.1 Effect of lateral spacing of piers on their wake

Paint impressions studies were carried when the piers were laterally spaced at Z/D = 2, 4, 6 and 8. Figures 4.11(a) shows the photographs of the paint impressions for lateral spacing of piers for Z/D = 4, 6 and 8. Figures 4.11(b) shows the Xerox of the paint impressions at reduced scale. These figures indicate the growth of the separation zone around the cylindrical piers and their wake development downstream of the cylinder. It may be observed that the wake merging position and their wake widths depends on the lateral spacing of the piers

4.6.2 Effect of lateral spacing of upstream piers on the scour depth of downstream pier

Experiments were carried out keeping lateral space of upstream pier fixed and downstream pier located along the centre line of the spacing in the flow direction. For each set of run and given lateral spacing of upstream piers, the downstream pier position was changed for values of X/D = 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 14, 18, 22 and 26 measured from the upstream cylindrical piers, maintaining same flow conditions. Each experimental run was carried for 600 minutes. The maximum scour depth measured during the experimental period is considered for analysis.

In the first case, the lateral spacing at the upstream was kept fixed at Z/D = 2, for X/D = 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 14, 18, 22, 26 and flow conditions were Fr = 0.17 to 0.185. In Figure 4.12(a), it is observed that maximum scour depth at upstream Hs(u/s)/D (left and right)

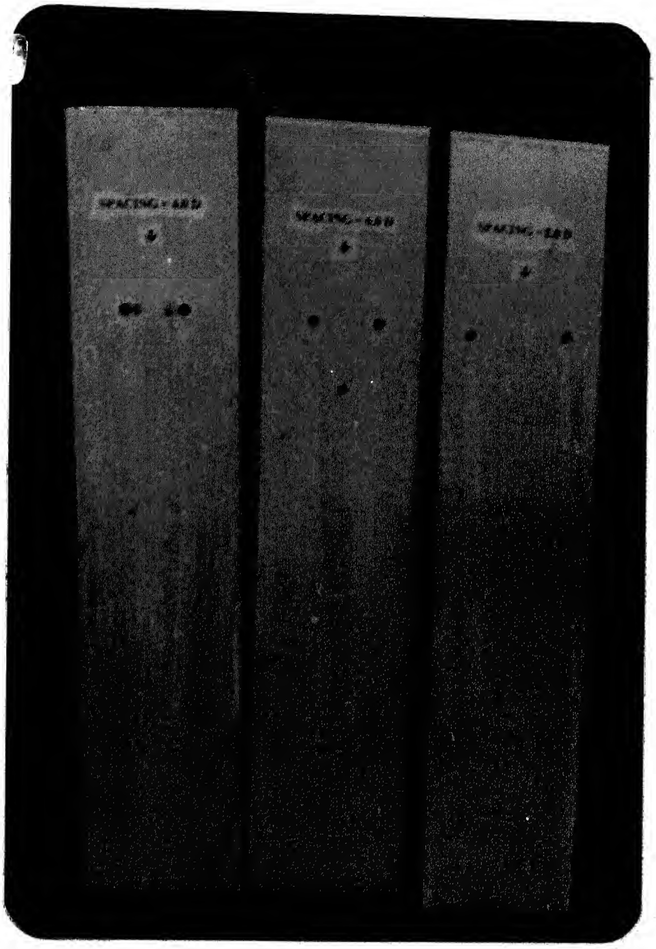


Fig: 4.11 (a)
PHOTOGRAPH OF WAKE BEHIND CIRCULAR CYLINDER PLACED SIDE BY SIDE
Z/D = 4, 6 AND 8

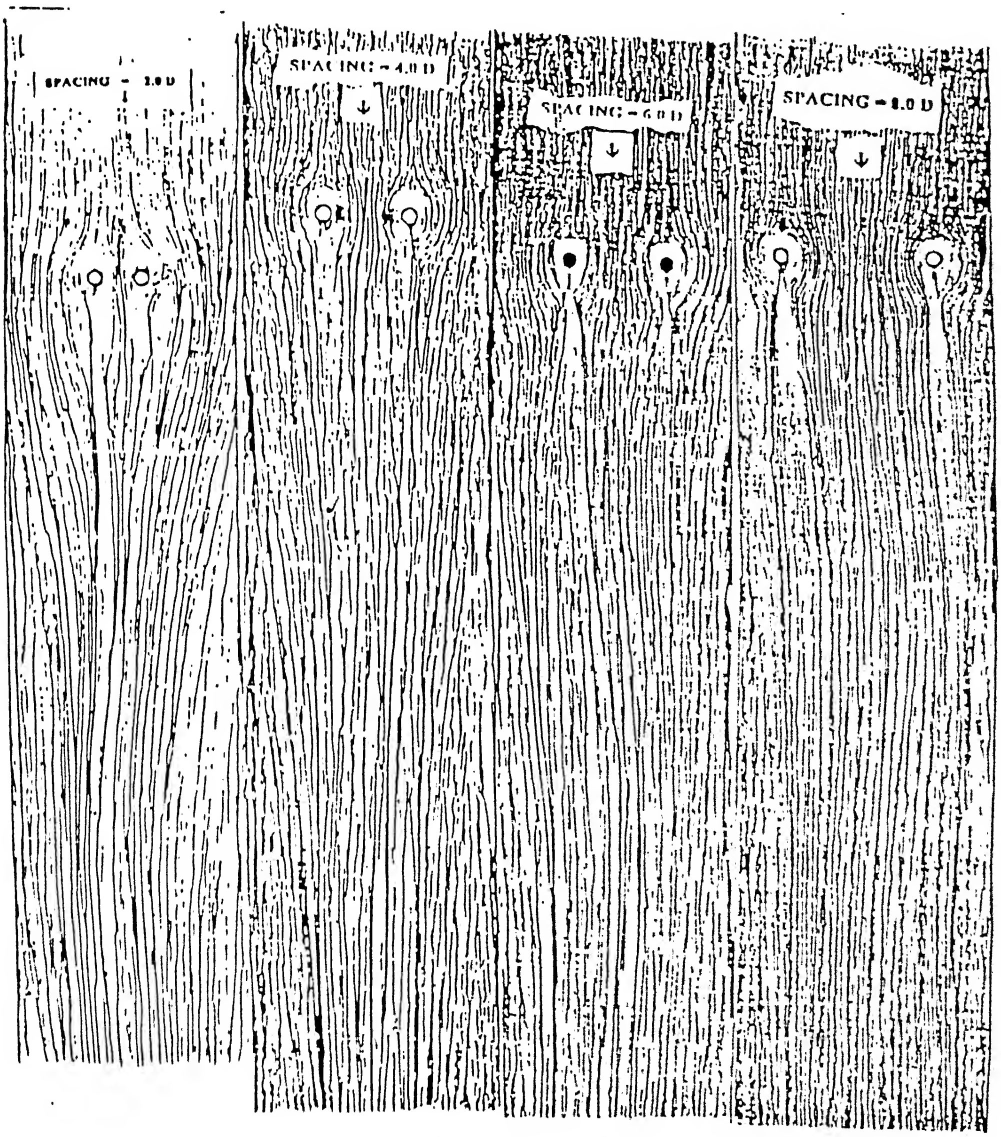


Fig: 4.11 (b)
WET PAINT IMPRESSIONS OF THE WAKE BEHIND CIRCULAR CYLINDERS
PLACED SIDE BY SIDE FOR Z/D = 2, 4, 6, 8

is plotted against X/D. The scour depth reaches maximum for upstream(left) and upstream(right) at X/D =1 and X/D = 10 respectively. The upstream scour depths fluctuates till X/D ≤ 18 and thereafter remains constant. In Figure 4.12(b) the maximum scour depth at downstream pier, Hs/D(d/s) is plotted against Z/D. It reaches maximum at X/D = 3, then it slowly decreases till X/D = 5, thereafter it increases upto X/D = 7. When X/D >10, the scour depth remains constant. The maximum scour depth(Hsd) at downstream pier is non-dimensionalised with maximum scour depth (Hsu) of upstream pier i.e. Hsd/Hsu plotted against X/D as shown in Figure 4.12(c). Magnitude of this ratio is highest at X/D ≈2, starts decreasing upto X/D = 5, further onwards remains constant. It may be concluded that the effect of upstream pier interference dominating on downstream pier till X/D ≈ 5.

In the second case when Z/D = 4, for X/D = 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 14, 18, 22, 26, 30, 34, 38, 42, 46, 50 flow conditions were Fr = 0.11 to 0.16. In Figure 4.13a, it is observed that maximum scour depths at upstream Hs(u/s)/D(left and right) are plotted against X/D. The scour depth reaches maximum for upstream(right) at X/D = 2 and fluctuates upto X/D ≈ 14. Thereafter, the scour depth remains constant. The maximum scour depth at downstream pier, Hs/D(d/s) is plotted against X/D in Figure 4.13(b) which reaches maximum at X/D = 18, i.e. the interference effect of flow are valid till X/D < 18. Thereafter, the scour depth remains constant. The maximum scour depth(Hsd) at downstream pier is non-dimensionalised with maximum scour depth (Hsu) of upstream pier i.e., Hsd/Hsu plotted against X/D for Fr = 0.11 to 0.16,as shown in Figure 4.13(c). The position of maximum value of the ratio occurs at X/D≈6 and fluctuates till X/D = 14 and remains fairly constant further onwards. Figure 4.13(c) shows variation of the scour depth of downstream pier for different X/D values. Fluctuations in the magnitude of scour depths persists upto X/D≈ 14, further onwards remains constant. Figure 4.13(c) show the variation of relative scour depths. For X/D>14, this ratio appears to reach stable value.

In the third case, when Z/D = 6.0, for X/D = 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 14, 18, 22, 26, 30, 34, 38 flow conditions were Fr = 0.11 to 0.19. In Figure 4.14(a), it may be observed that maximum scour depth at upstream, Hs(u/s)/D is plotted against X/D. The scour depth is maximum for upstream(left) and upstream(right) at X/D = 10 and X/D = 8 respectively.

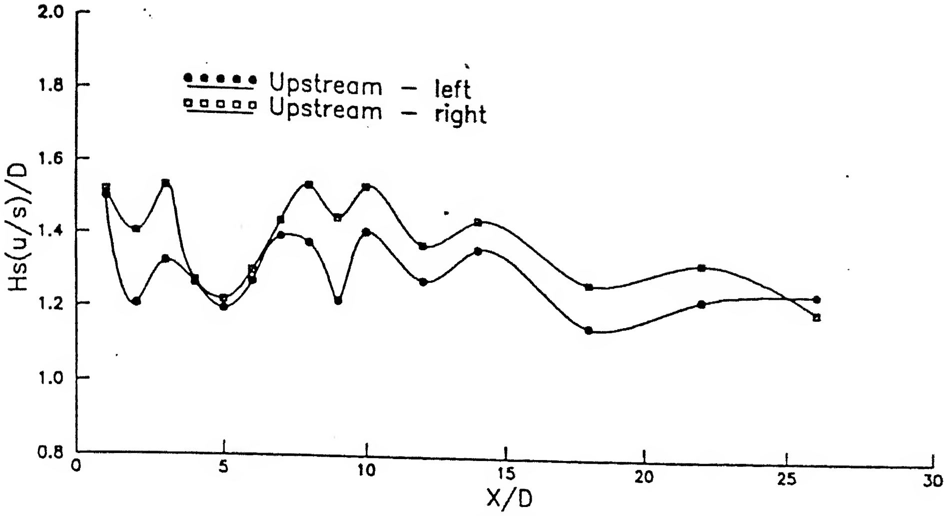


Fig: 4.12a

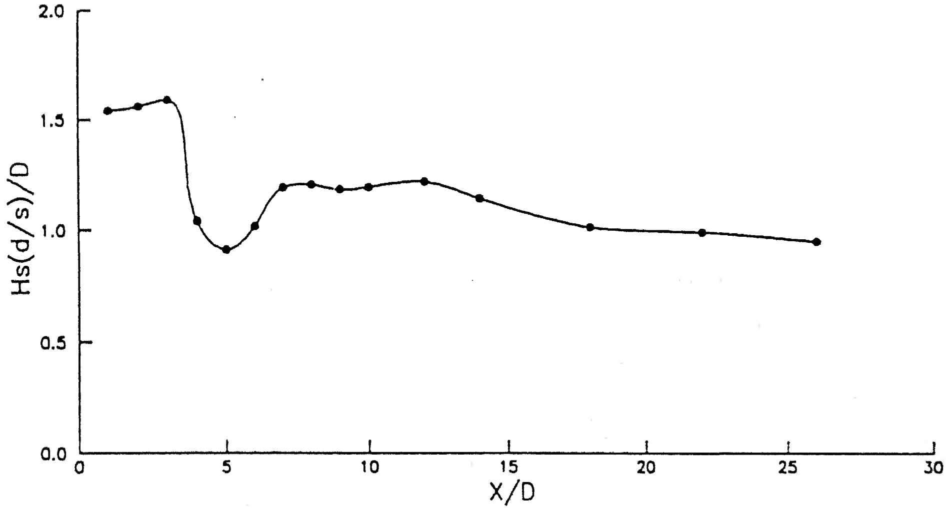


Fig: 4.12b

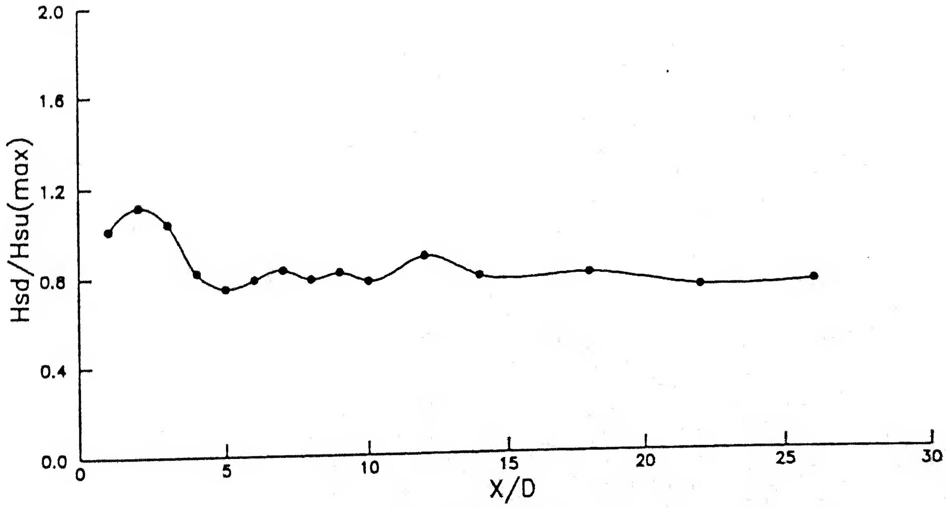


Fig: 4.12c

Fig: 4.12a to 4.12c

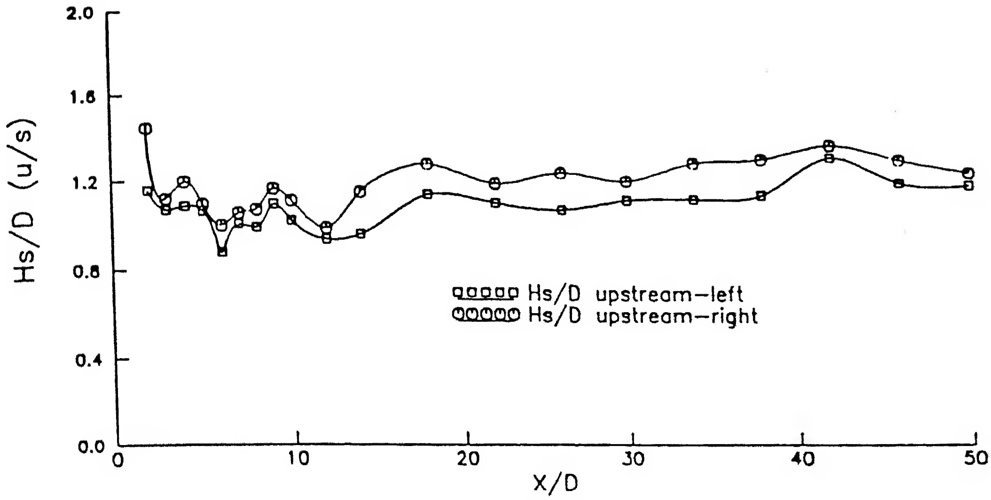


Fig: 4.13a

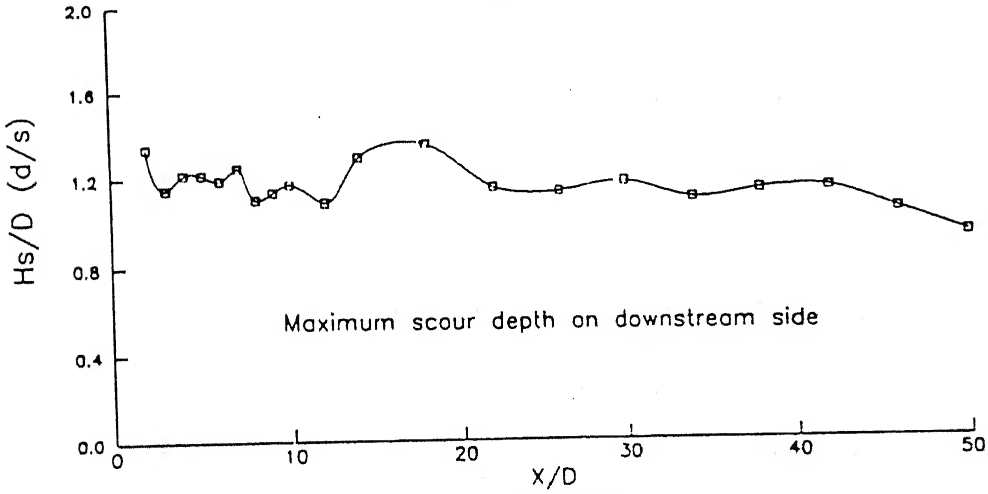


Fig: 4.13b

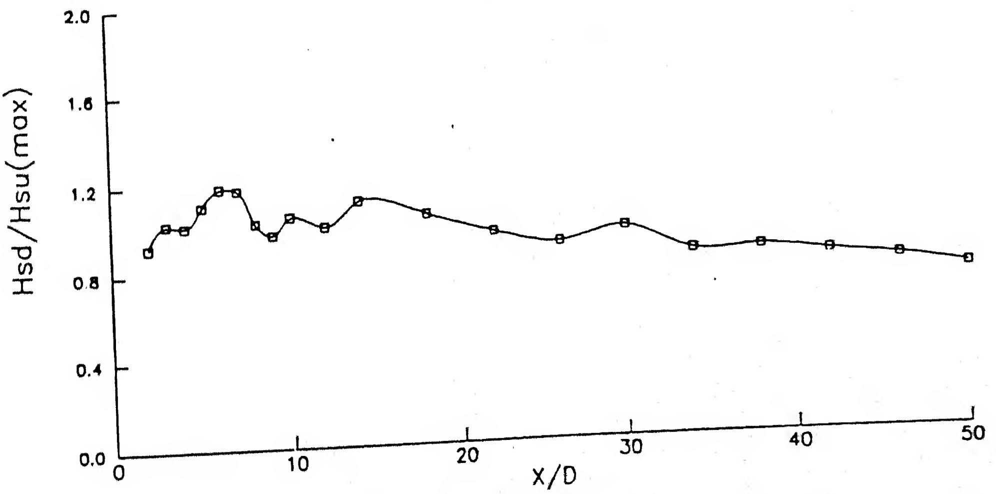


Fig: 4.13c

Fig: 4.13a to 4.13c

SCOUR DEPTH VARIATIONS OF UPSTREAM AND DOWNSTREAM PIERS FOR STAGGERED ARRANGEMENT PATTERN - II, WHEN Z/D = 4

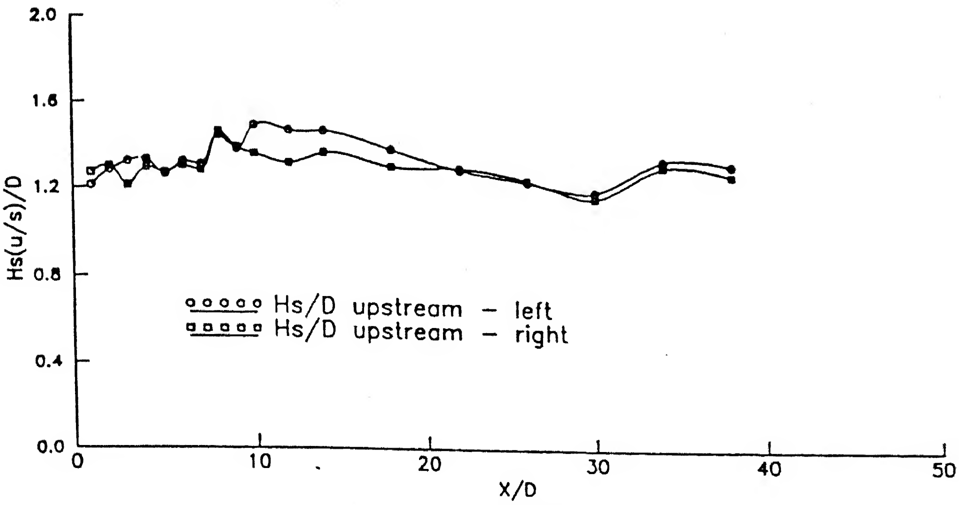


Fig: 4.14a

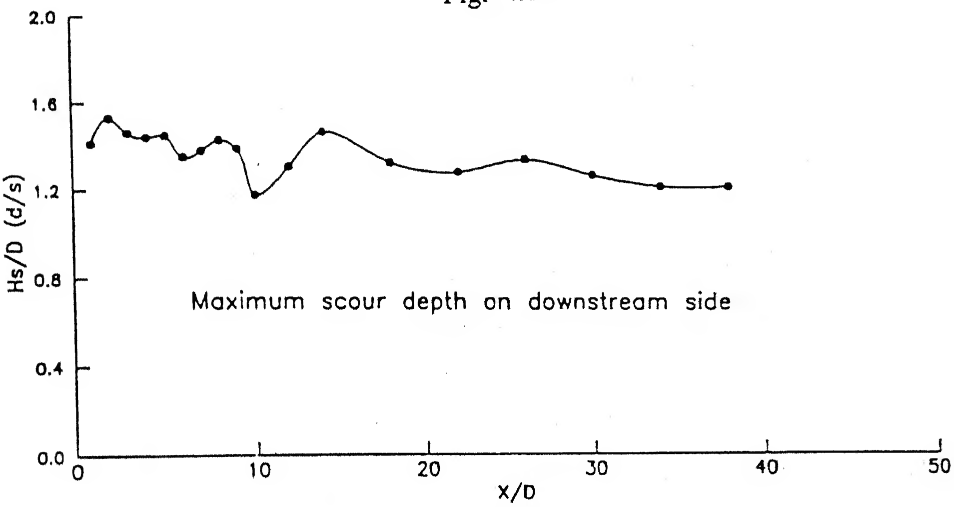


Fig: 4.14b

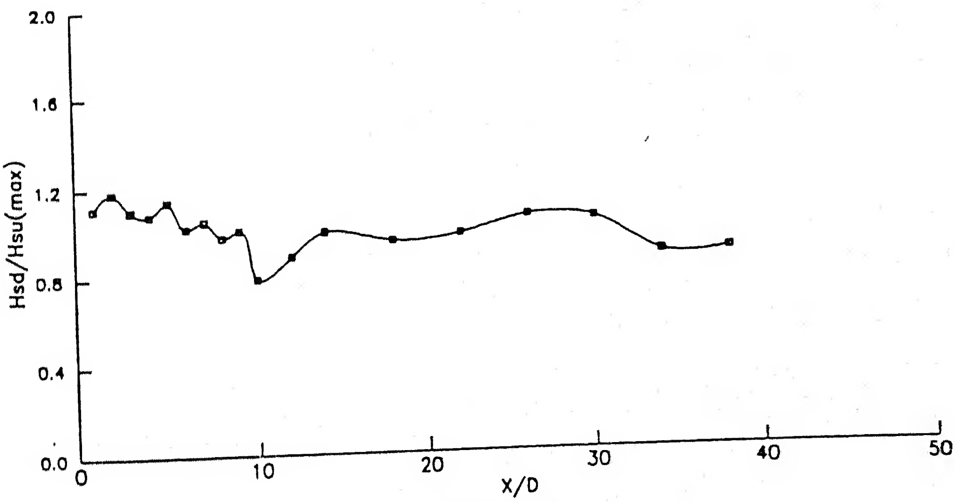


Fig: 4.14c

Fig: 4.14a to 4.14c

SCOUR DEPTH VARIATIONS OF UPSTREAM AND DOWNSTREAM PIERS FOR STAGGERED ARRANGEMENT PATTERN - II , WHEN Z/D = 6

The interference effects of flow are valid till X/D < 14. Thereafter, the scour depth remains constant.

In the fourth case of Z/D = 8, for X/D = 1 to 50 and Fr = 0.13 to 0.16 , the scour depth values are plotted in the Figures 4.15(a),(b) and (c). The magnitude of scour depths of upstream piers remains almost same for all the positions of downstream pier as shown in Figure 4.15(a). The variation of scour depth values for downstream pier is plotted in Figure 4.15(b). The maximum magnitude of scour depth occurred at X/D = 3, and at all the other values of X/D, this magnitude is comparatively less. The relative scour depth of downstream pier with respect to upstream pier remains fairly same for all the values of X/D as shown in Figure 4.15(c)

4.6.3 Erosion or Deposition Pattern Between Upstream and Downstream Piers of Staggered Arrangement (Pattern - II)

The bed profiles measured between upstream pier and downstream pier of staggered arrangement - II are plotted in Figure 4.16 for Z/D = 2. It may be observed that erosion is dominating longitudinal spacing X/D = 3. Deposition starts occurring in between the piers for X/D >3 to X/D = 6, later on the deposition occurs, but its magnitude is not dominating. The maximum deposition occurs near the downstream pier for X/D >12 and its magnitude of deposition is of order 3/4D

In the Figure 4.17 for Z/D = 4, may be observed that the erosion is dominating upto longitudinal spacing X/D = 4. Deposition starts occurring in between the piers for X/D > 4 and it dominates at X/D = 7. Later on the deposition occurs, but its magnitude is not dominating. These observations can be seen in Figure 4.17. As X/D increases further to X/D > 18, the leveling of the bed occurs similar to occurrence of bed forms without any interference of piers.

Erosion and deposition patterns between upstream pier and downstream pier are plotted in Figure 4.18 for Z/D = 6. Erosion is dominating intermittently upto X/D = 8. For X/D > 8, deposition starts dominating, maximum deposition occurs near the downstream pier for X/D > 22. The magnitude of deposition is of order 3/4D.

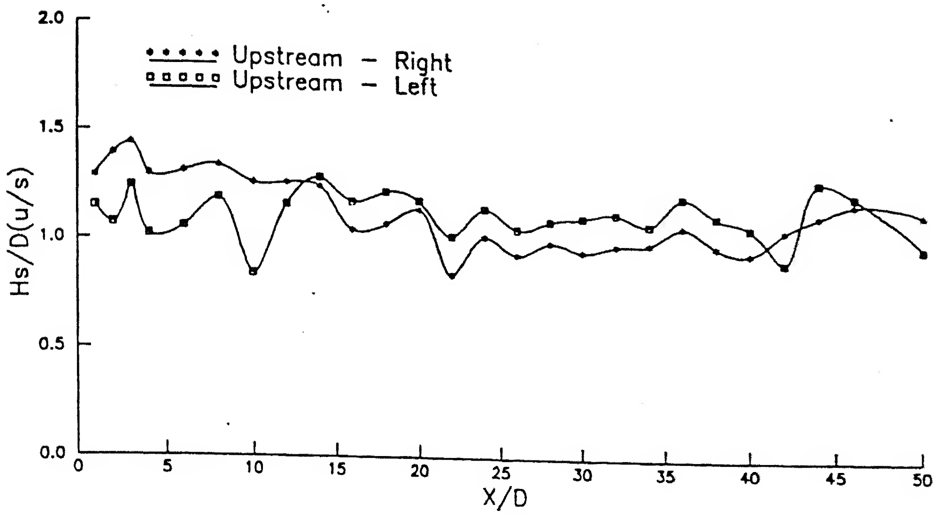


Fig: 4.15a

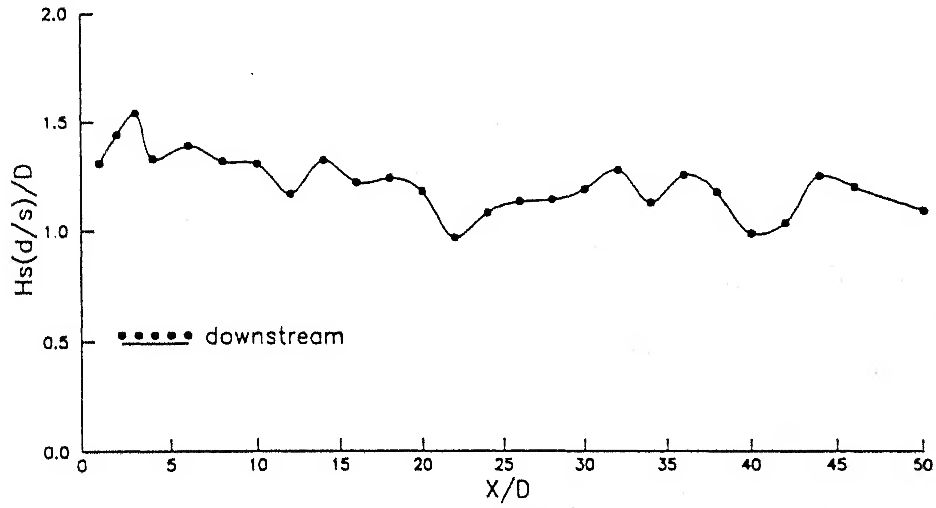


Fig: 4.15b

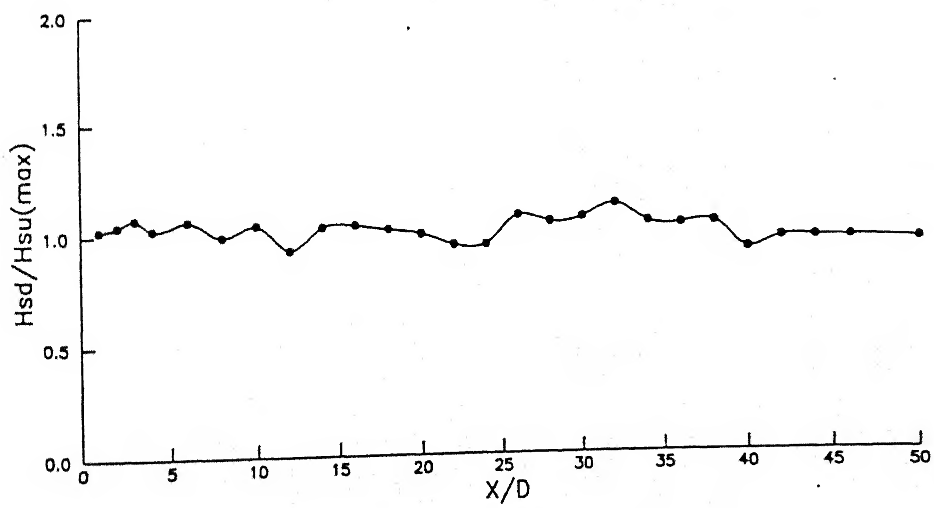


Fig: 4.15c

Fig: 4.15a to 4.15c

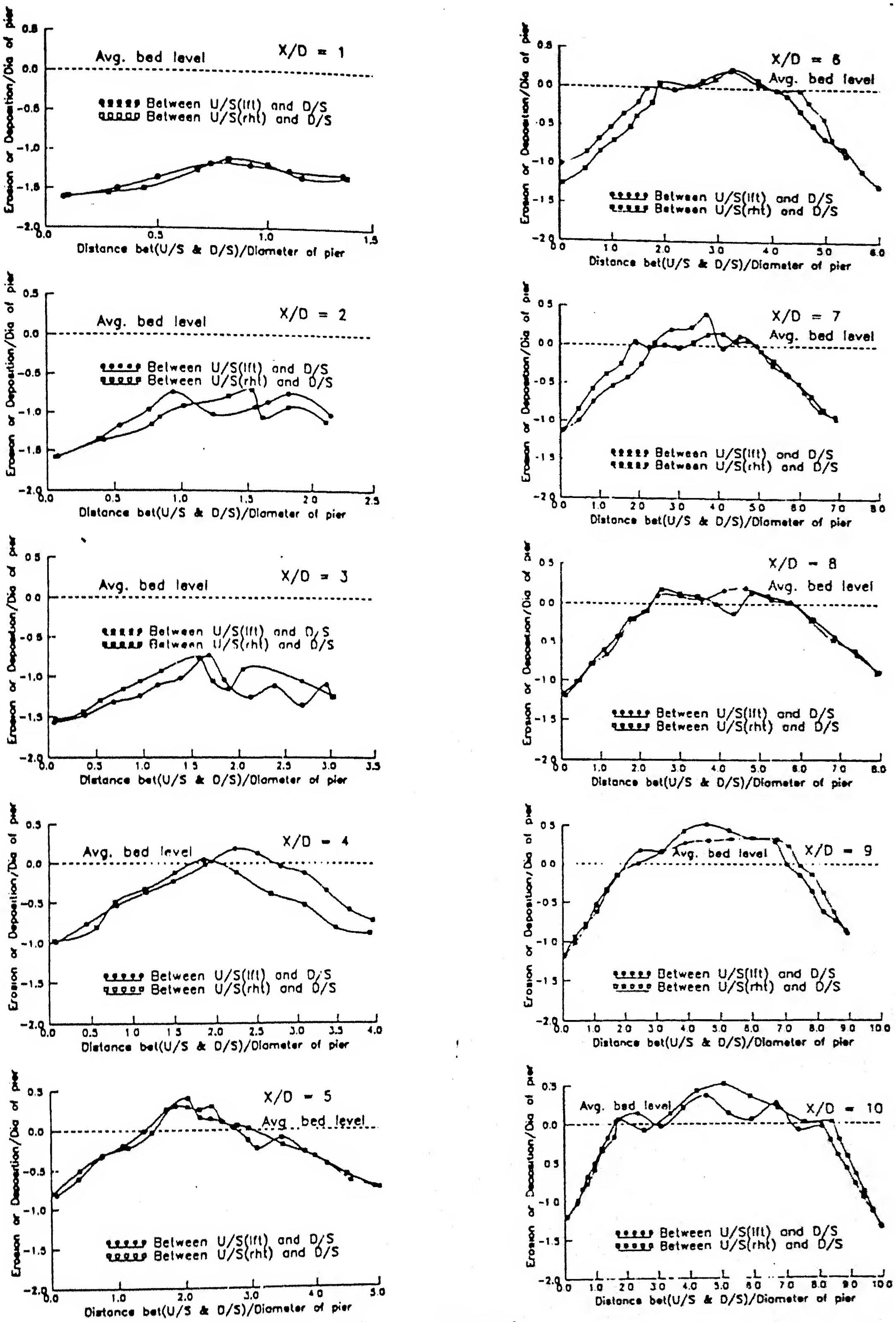


Fig: 4.16

EROSION AND DEPOSITION OF SEDIMENT BED PROFILES BETWEEN THE UPSTREAM PIERS AND DOWNSTREAM PIER FOR STAGGERED ARRANGEMENT (PATTERN - II), WHEN Z/D = 2

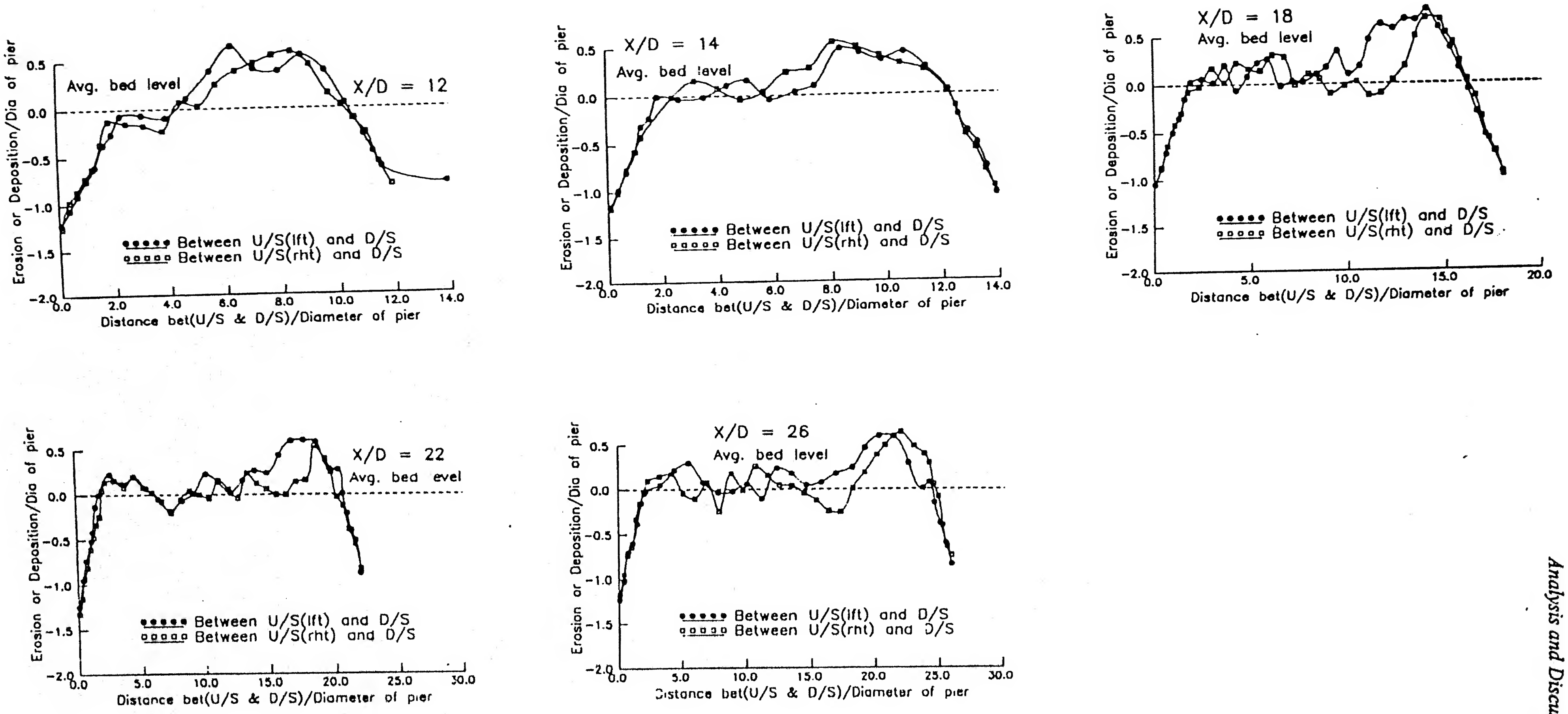


Fig: 4.16
EROSION AND DEPOSITION OF SEDIMENT BED PROFILES BETWEEN THE UPSTREAM PIERS AND DOWNSTREAM PIER FOR STAGGERED ARRANGEMENT (PATTERN - II), WHEN Z/D = 2

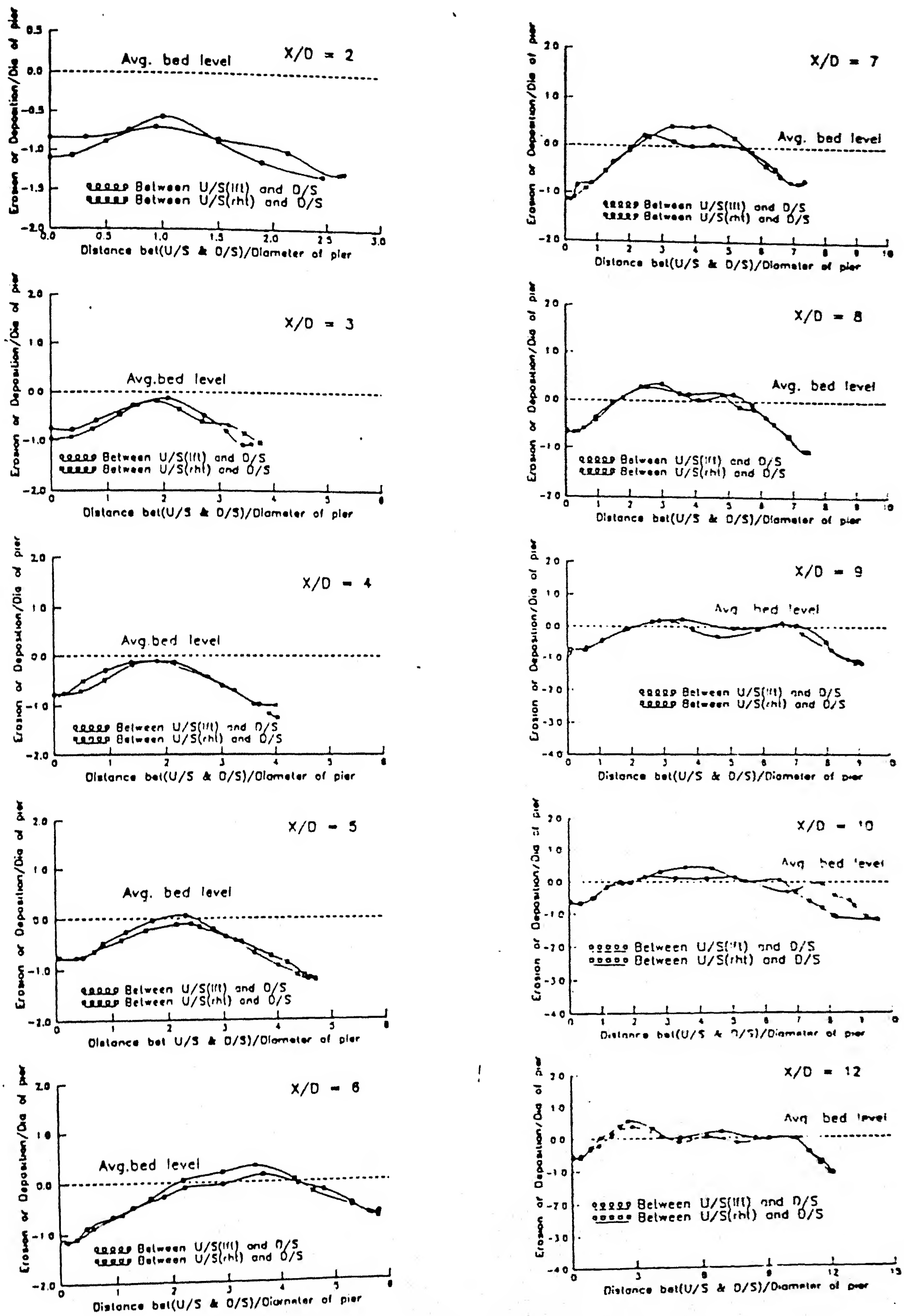


Fig: 4.17

EROSION AND DEPOSITION OF SEDIMENT BED PROFILES BETWEEN THE UPSTREAM PIERS AND DOWNSTREAM PIER FOR STAGGERED ARRANGEMENT (PATTERN -II), WHEN Z/D = 4

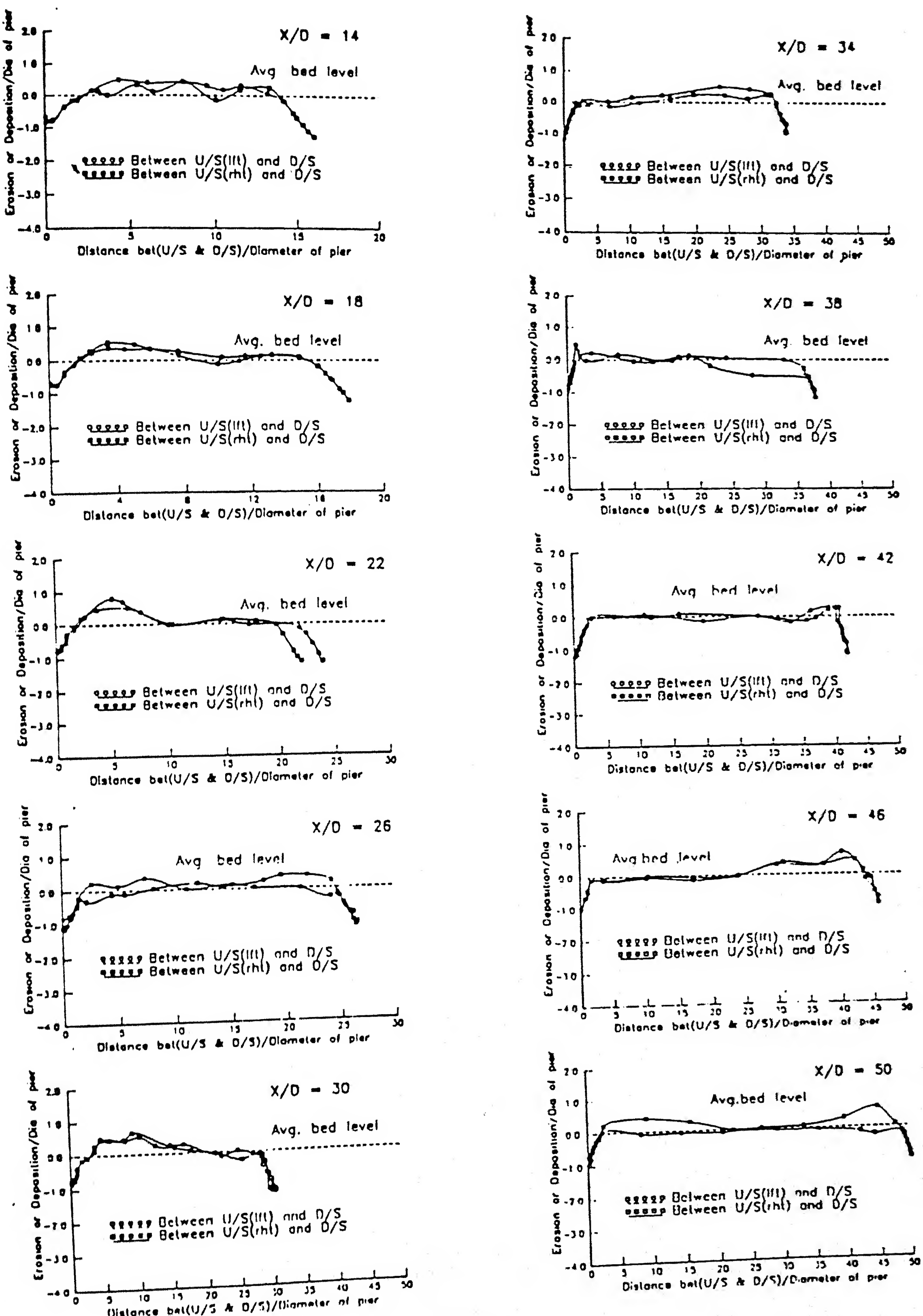


Fig: 4.17

EROSION AND DEPOSITION OF SEDIMENT BED PROFILES BETWEEN THE UPSTREAM PIERS AND DOWNSTREAM PIER FOR STAGGERED ARRANGEMENT (PATTERN -II), WHEN Z/D = 4

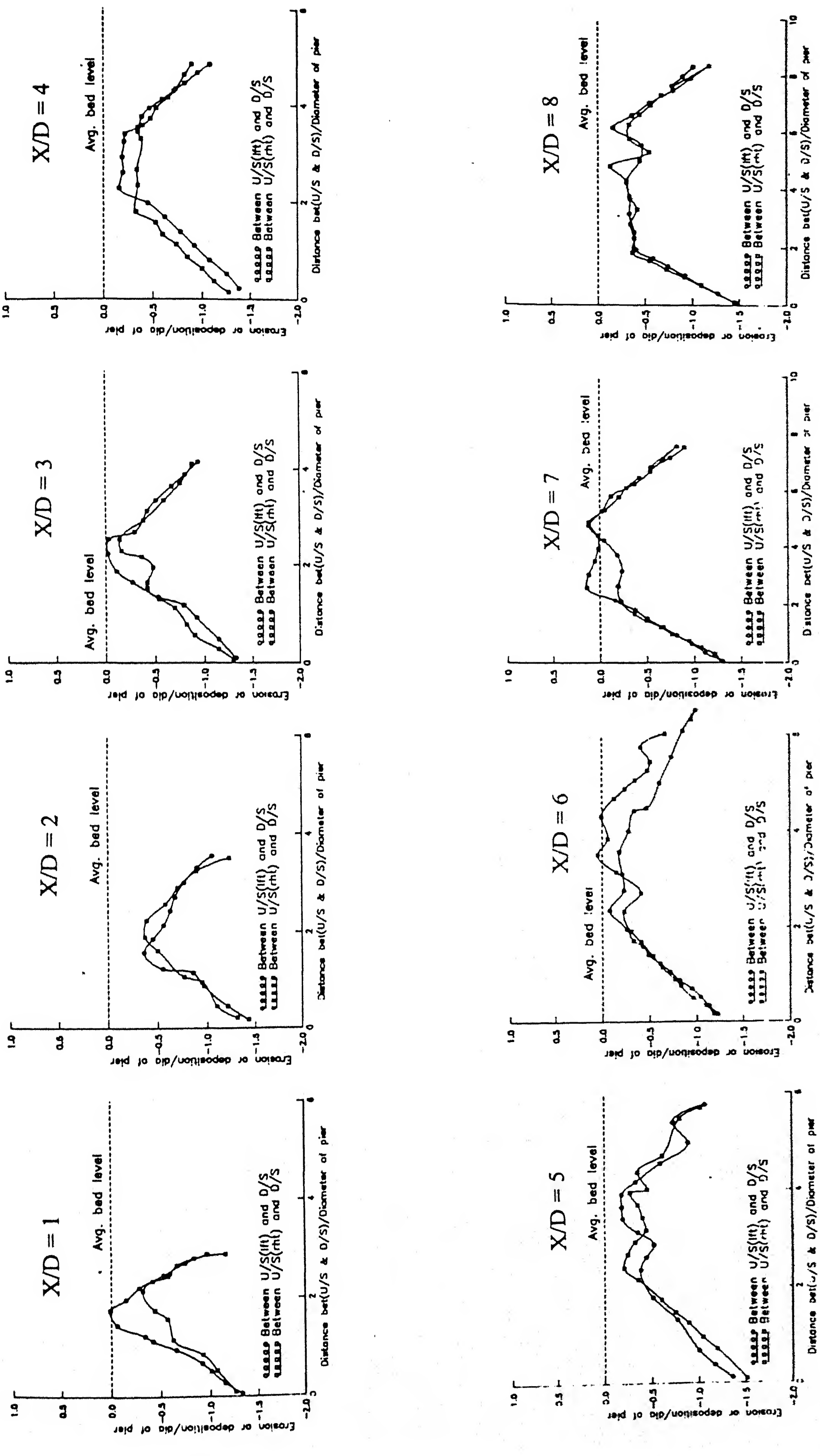


Fig: 4.18
EROSION AND DEPOSITION OF SEDIMENT BED PROFILES BETWEEN THE UPSTREAM PIERS AND DOWNSTREAM PIER FOR STAGGERED ARRANGEMENT (PATTERN - II), WHEN Z/D = 6

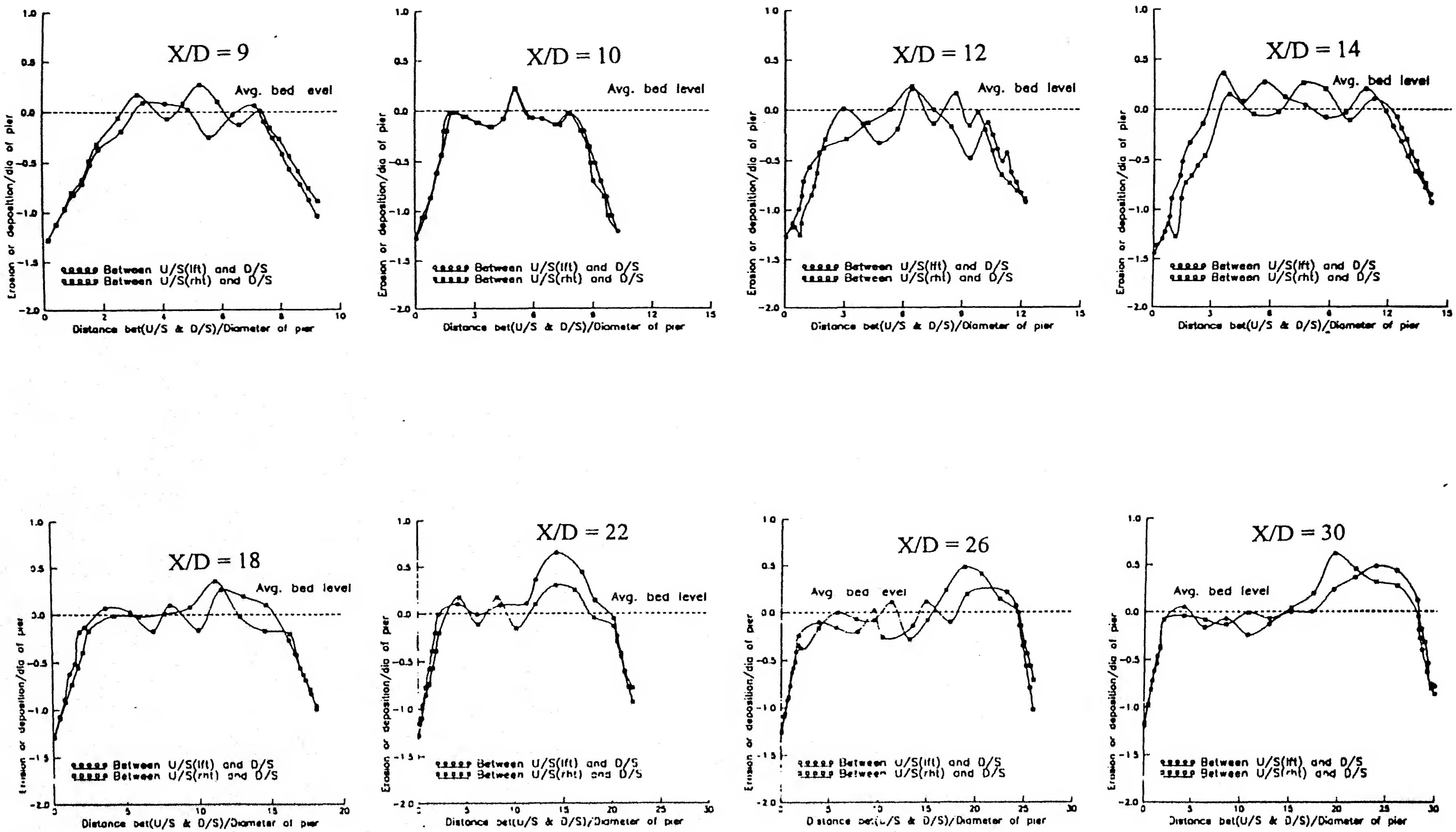
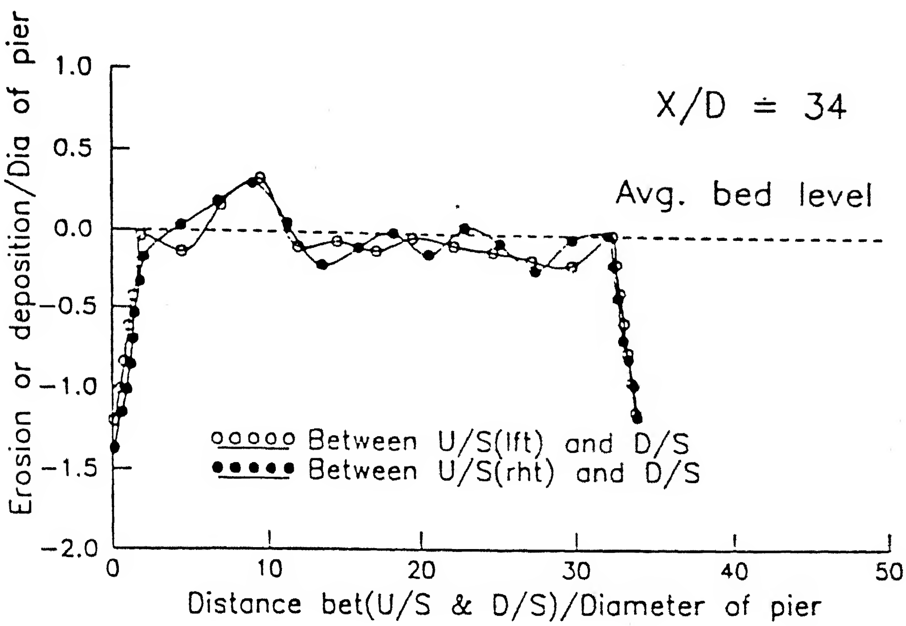


Fig: 4.18
EROSION AND DEPOSITION OF SEDIMENT BED PROFILES BETWEEN THE UPSTREAM PIERS AND DOWNSTREAM PIER FOR STAGGERED ARRANGEMENT (PATTERN - II), WHEN Z/D = 6



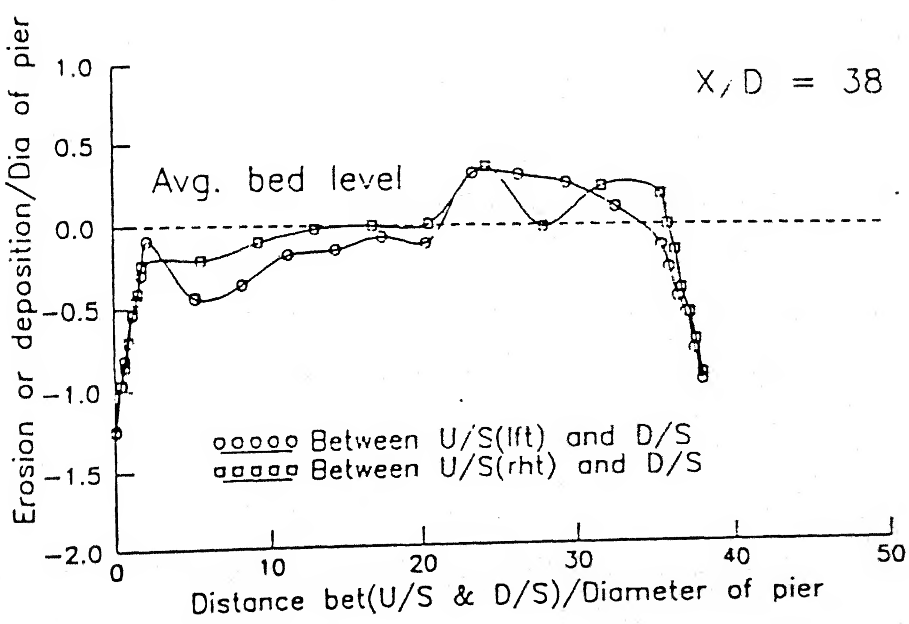


Fig: 4.18

EROSION AND DEPOSITION OF SEDIMENT BED PROFILES BETWEEN THE UPSTREAM PIERS AND DOWNSTREAM PIER FOR STAGGERED ARRANGEMENT (PATTERN - II), WHEN Z/D = 6

From Figures 4.16, 4.17 and 4.18, it may be observed that as the lateral spacing Z/D of the upstream pier increases, the zone of erosion decreases. However the magnitude of highest erosion decreases with increase in lateral spacing of upstream piers.

4.6.4 Interference Effect of Staggered Arrangement Pattern - II

Interference effect for staggered arrangement pattern- II is carried out by considering the ratios of difference in scour depths between the maximum value of any upstream pier with the downstream pier scour depth to the upstream pier scour depth. It is denoted as I.E. The interference effect values for each lateral spacing of piers are shown separately.

Lateral spacing: Z/D = 2

The interference effect I.E is plotted for staggered arrangement (pattern - II) for Z/D = 2, against different values of X/D in Figure 4.19. It may be observed that I.E attains negative maximum at X/D = 2 and is of the order of 0.11. This may be considered as dangerous zone. As X/D increases, the magnitude of I.E becomes zero around X/D = 3.5. With further increase in X/D, the magnitude of I.E becomes positive and is of the order 0.25. The location of downstream pier for X/D>3.5, can be considered to be safe.

Lateral spacing: Z/D = 4

The Figure 4.20 shows the interference effect variation with downstream pier location for staggered arrangement pattern - II at Z/D = 4. It may be observed that I.E attains negative maximum around X/D = 4. As X/D increases, the magnitude of I.E recovers and becomes zero around X/D = 18. With further increase in X/D, the magnitude of I.E becomes positive . The zone of negative I.E is considered as dangerous zone. This zone lies within X/D < 18. The highest magnitude of I.E observed was -0.2.

Lateral spacing: Z/D = 6

Interference effect I.E is plotted for staggered arrangement pattern - II for Z/D = 6, in the Figure 4.21. Negative zone of interference occurs upto X/D ≤ 10and it fluctuates between 10 < X/D < 35. The highest magnitude of I.E is of the order of -0.2, which occurs around X/D =2. The zone of positive I.E values occurs intermittently between X/D = 12 to 15 and 16 to 22 and 32 onwards. Maximum positive I.E is of the order of 0.2 which occurs at X/D = 14.

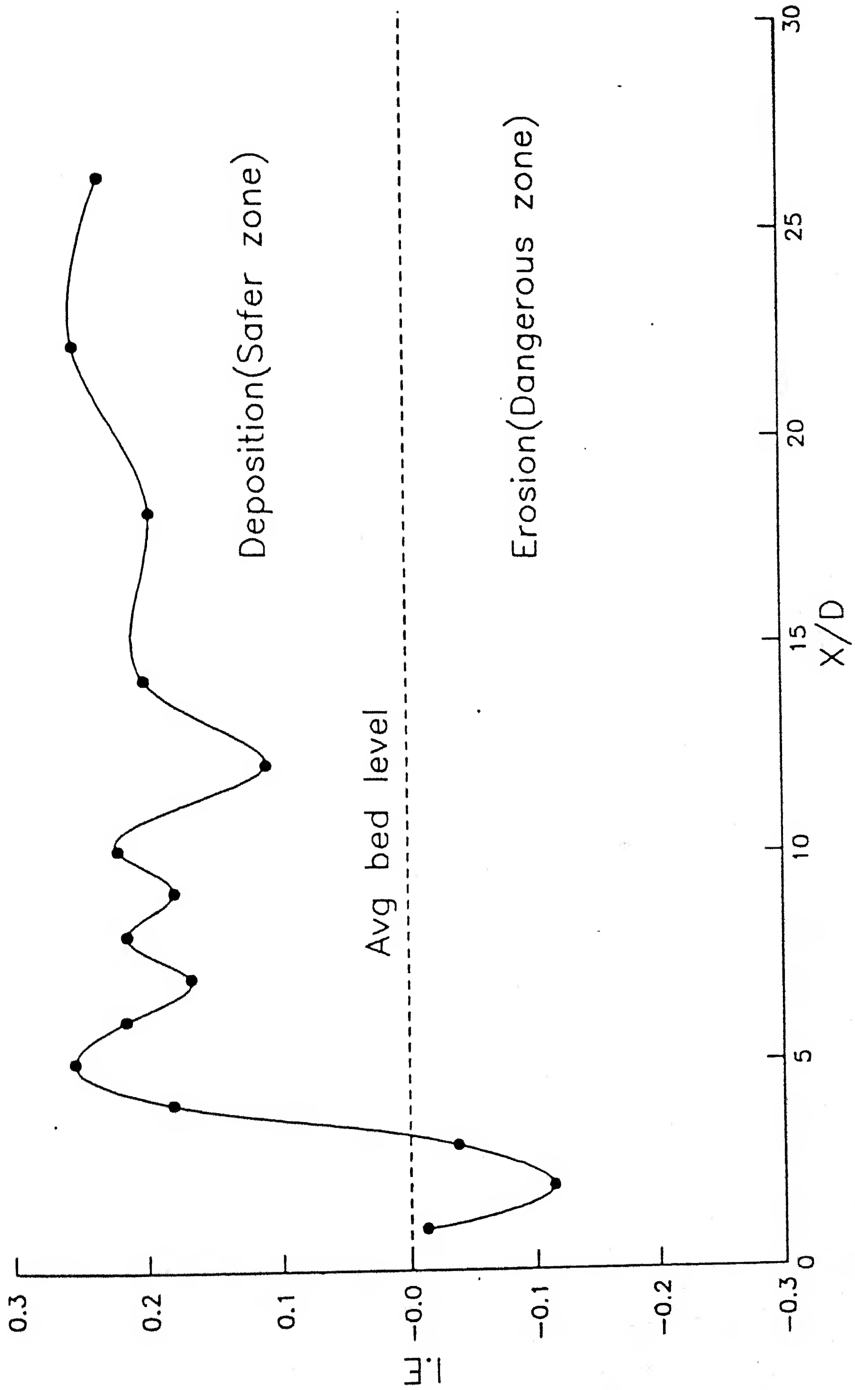


Fig: 4.19
INTERFERENCE EFFECT OF STAGGERED ARRANGEMENT (PATTERN - II)
WHEN Z/D = 2 AT DIFFERENT X/D VALUES

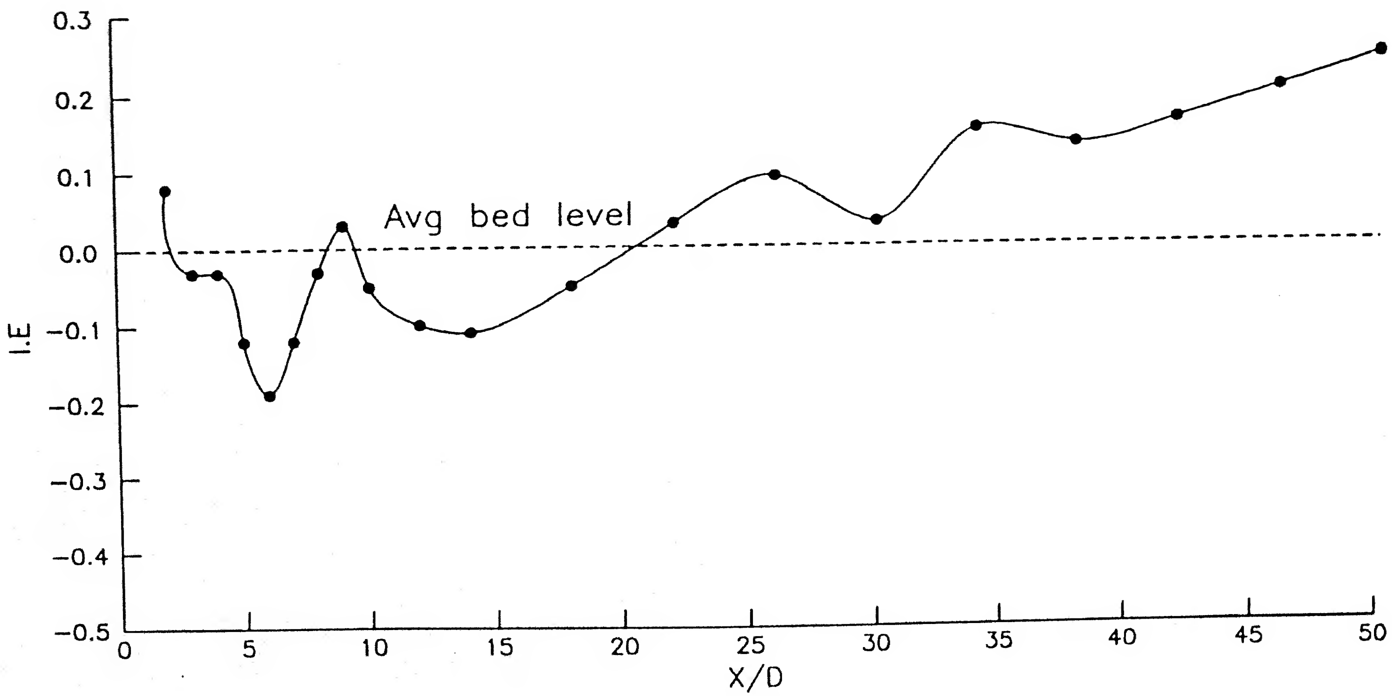


Fig: 4.20
INTERFERENCE EFFECT OF STAGGERED ARRANGEMENT (PATTERN - II) WHEN Z/D = 4 AT DIFFERENT X/D VALUES

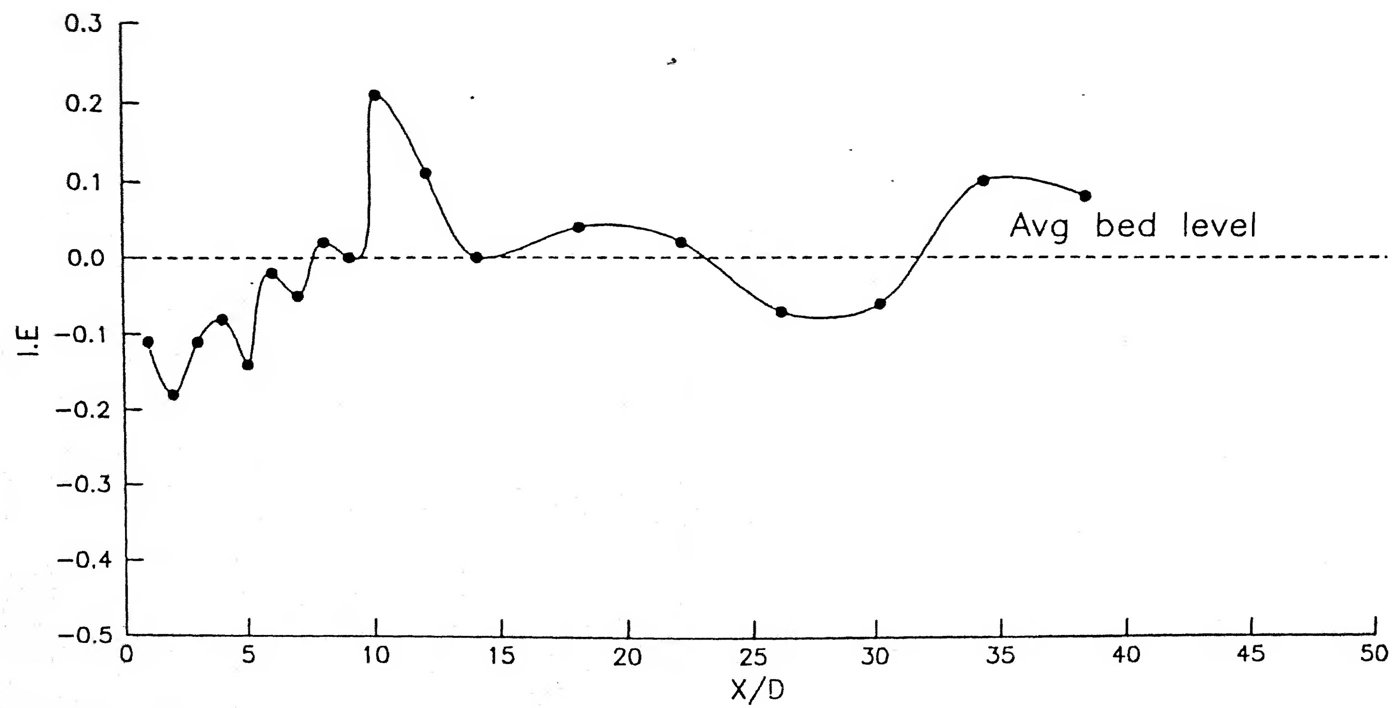


Fig: 4.21
INTERFERENCE EFFECT OF STAGGERED ARRANGEMENT (PATTERN - II)
WHEN Z/D = 6 AT DIFFERENT X/D VALUES

Lateral spacing: Z/D = 8

Interference effect I.E for staggered arrangement pattern-II for Z/D = 8 in the Figure 4.22 is plotted against various positions of downstream pier in terms of X/D values. The position of negative values of I.E occurs intermittently for the zones X/D<11, !4<X/D<20, 25<X/D<39. Position values of interference effect occurs intermittently for zone X/D<39, for zone X/D>39, continuously. Magnitude of maximum negative interference effect is of the order of -0.075 at X/D = 3, 6,26 and 30. Effect of interference of upstream cylindrical piers on downstream cylindrical piers extends upto X/D = 39.

4.6.5 Length and Intensity of The Interference Zone

The position upto which the negative value of interference effect extends along the centre line of spacing of piers is plotted in Figure 4.23. Length of negative interference effect zone extends almost linearly with the lateral spacing of the piers. The magnitude of the maximum negative interference effect is plotted with lateral spacing Z/D as shown in Figure 4.24. The heighest intensity of the interference effect found to occur in the lateral spacing around Z/D = 4 to 6. The magnitude of the maximum intensity of interference decreases on either side of Z/D≈ 4 to 6. The decrease in the maximum intensity interference with increase in Z/D values beyond 6 can be attributed to reduction in the magnitude of the velocity on the wake boundary. The reduction of I.E intensity for Z/D<4 may be due to effect of near wake of the upstream cylinders.

4.6.6 Effect of Lateral Spacing on Maximum Scour Depth

Scour depths of piers when they are closely spaced are subjected to interference of flow and change in magnitude of the separation zone formed around the piers. This resulted in increase in scour depths as the lateral spacing becomes reduces. To study the influence of lateral spacing on scour depth of piers, results of staggered pattern arrangement - II are considered for the analysis. In these cases, maximum scour depths of upstream piers when the downstream pier is located far away, is considered. These maximum scour depth are plotted in the Figure 4.25. It may be observed that the magnitude of maximum scour depth decreases as the lateral spacing increases. The increase in scour depth value for close spacing is due to interference of flow on the magnitude of scouring horseshoe vortex.

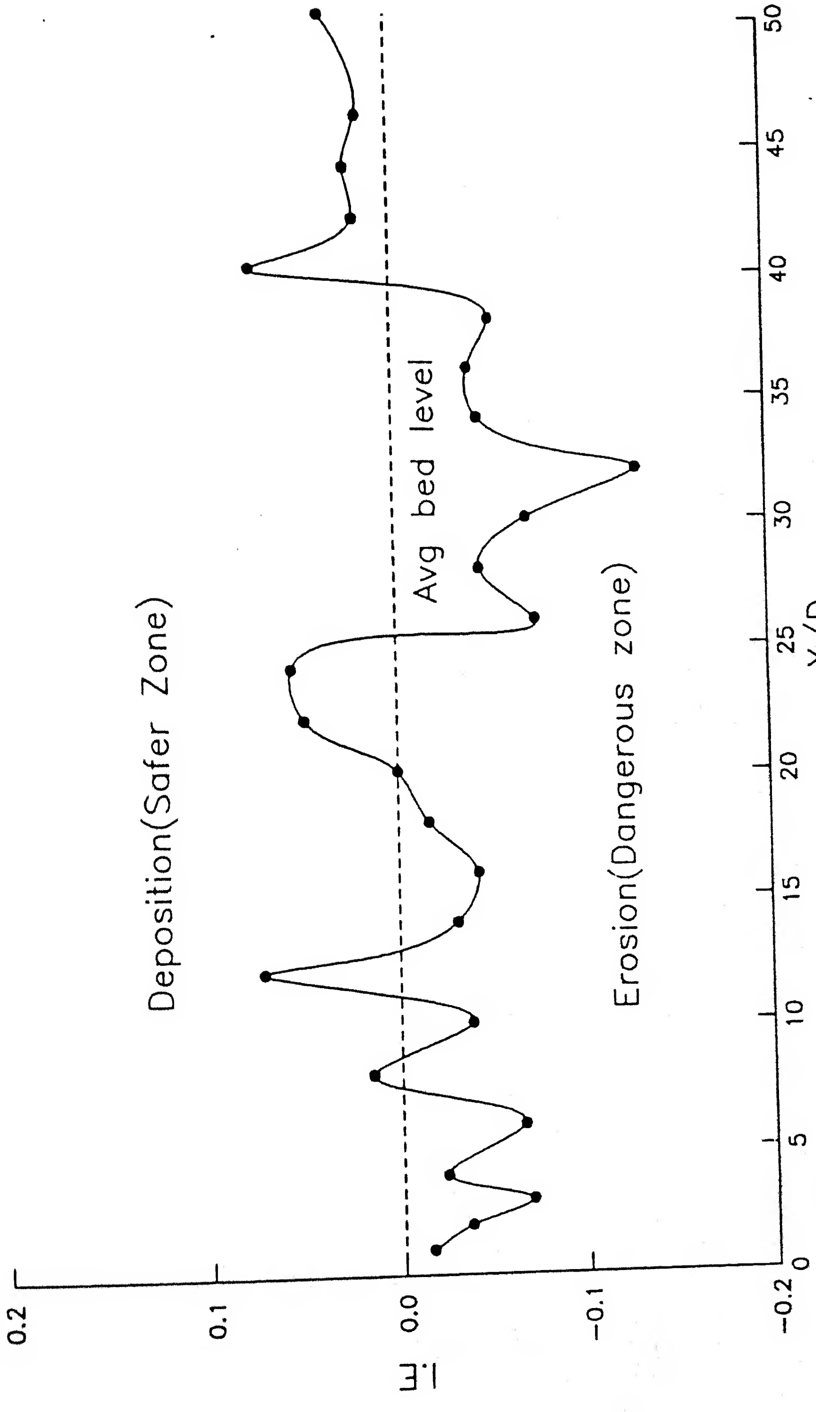
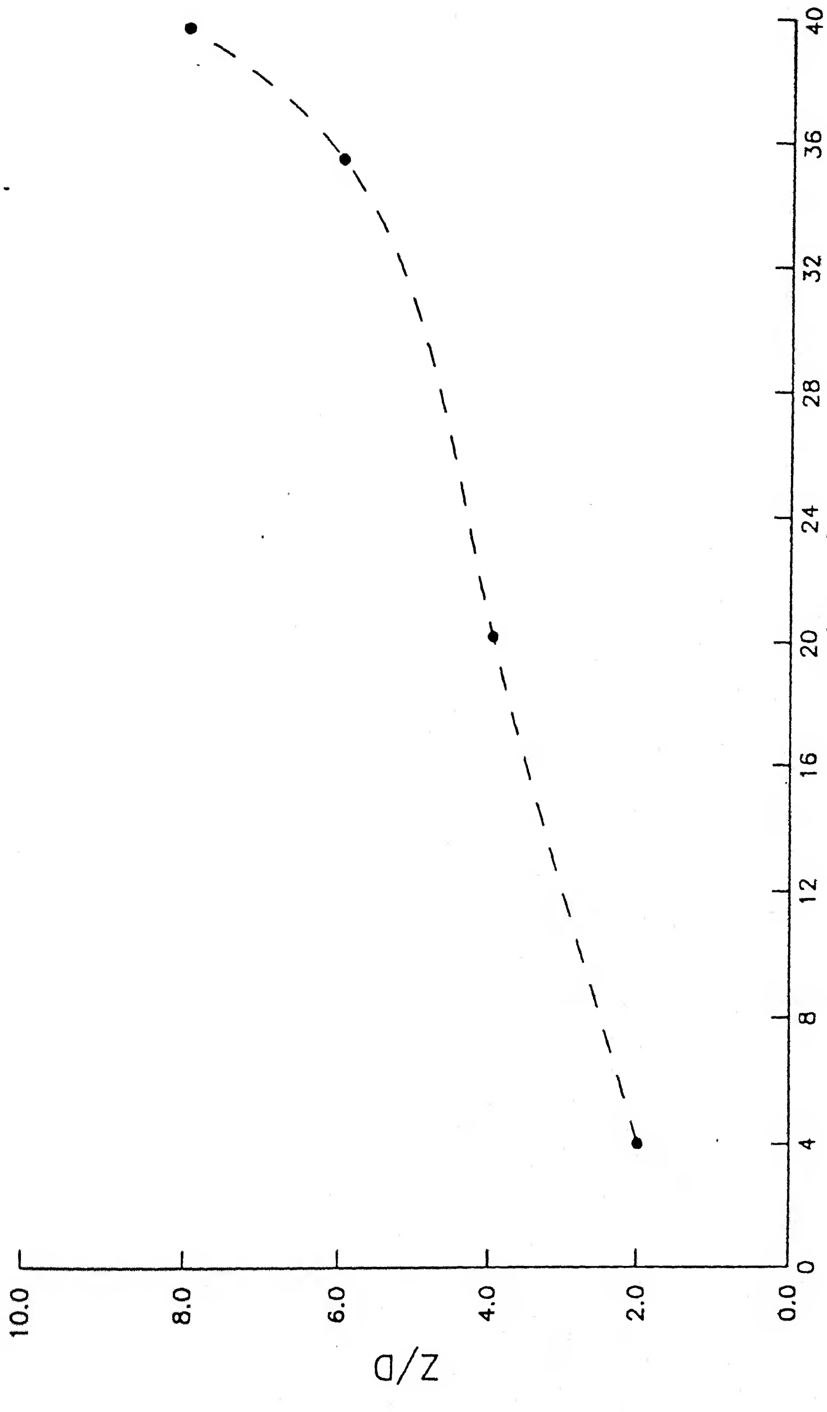


Fig: 4.22
INTERFERENCE EFFECT OF STAGGERED ARRANGEMENT (PATTERN - II)
WHEN Z/D = 8 AT DIFFERENT X/D VALUES



Fig; 4.23
LENGTH OF NEGATIVE INTERFERENCE ZONE AT CENTRE OF LINE OF SPACING OF PIERS FOR PATTERN - II

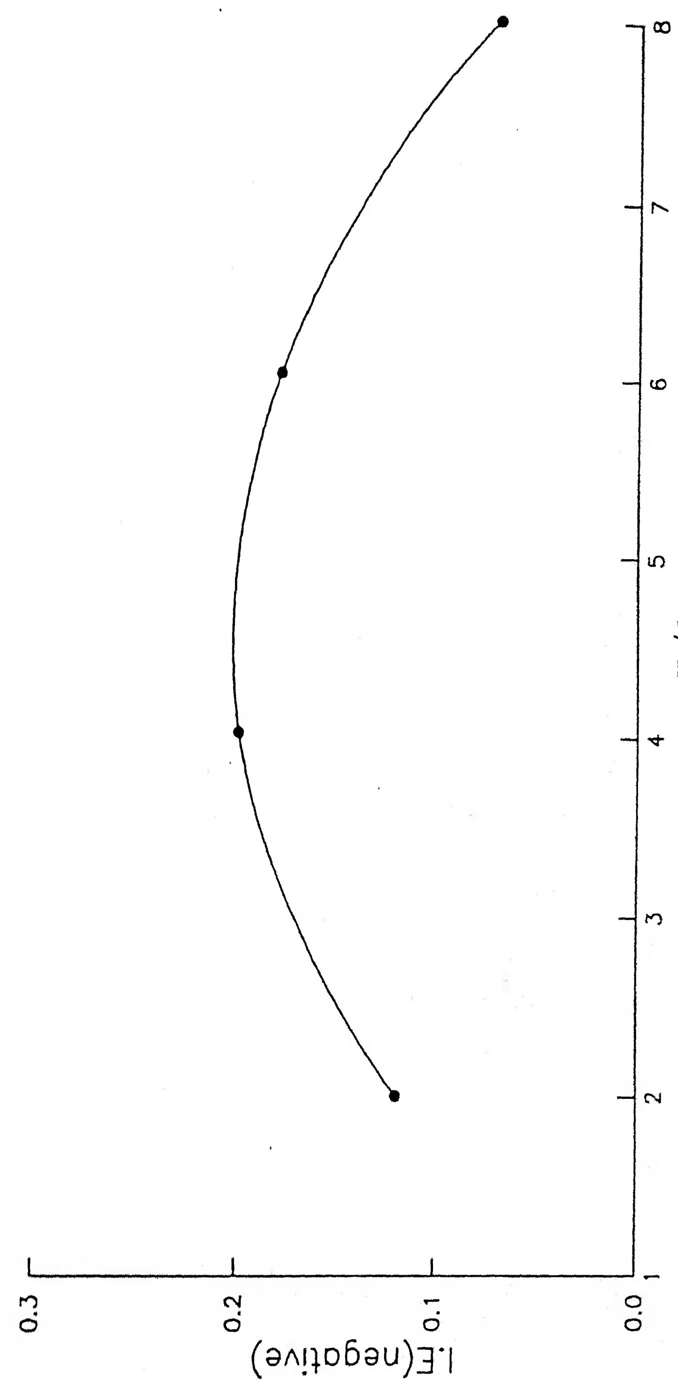


Fig: 4.24
VARIATION OF MAGNITUDE OF THE MAXIMUM NEGATIVE INTERFERENCE EFFECT FOR DIFFERENT LATERAL SPACING OF PIERS

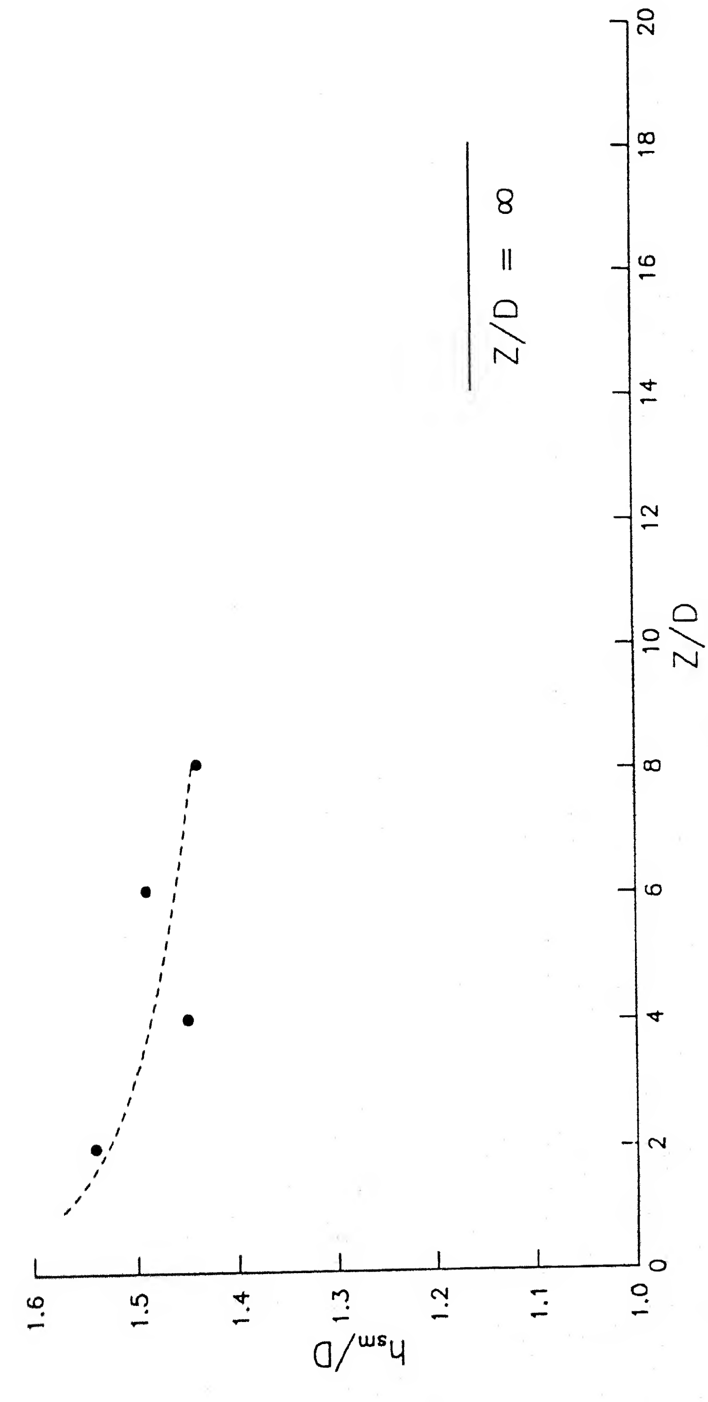


Fig: 4.25
EFFECT OF LATERAL SPACING ON MAXIMUM SCOUR DEPTH

Magnitude of the interference effect I.E is plotted against the lateral spacing Z/D as shown in Figure 4.26. The maximum interference at Z/D = 2 is of the order of 0.33 and decreases with increases in lateral spacing. This can be explained by the interference effect of drag of a circular cylinders held in free stream as shown in Figure 4.27. It may be observed that the magnitude of drag coefficient C_D is higher with a value equal to1.5, when Z/D = 0 and decreases upto Z/D≈0.8 to a value of C_D = 1.0. With further increase in Z/D the value of C_D increases to a magnitude of 1.3 around Z/D = 1.0. As Z/D increases, the magnitude of C_D decreases and attains a value nearly equal to 1.18, which is the value of single cylinder held in free stream. The change in magnitude of C_D is the result of the interference of flow on the pressure distribution on the surface of the cylinder. Similarly, the pressure distribution on the base plate of cylinder also gets modified, may result in higher value of C_D. This higher value of C_D results in higher scour depths.

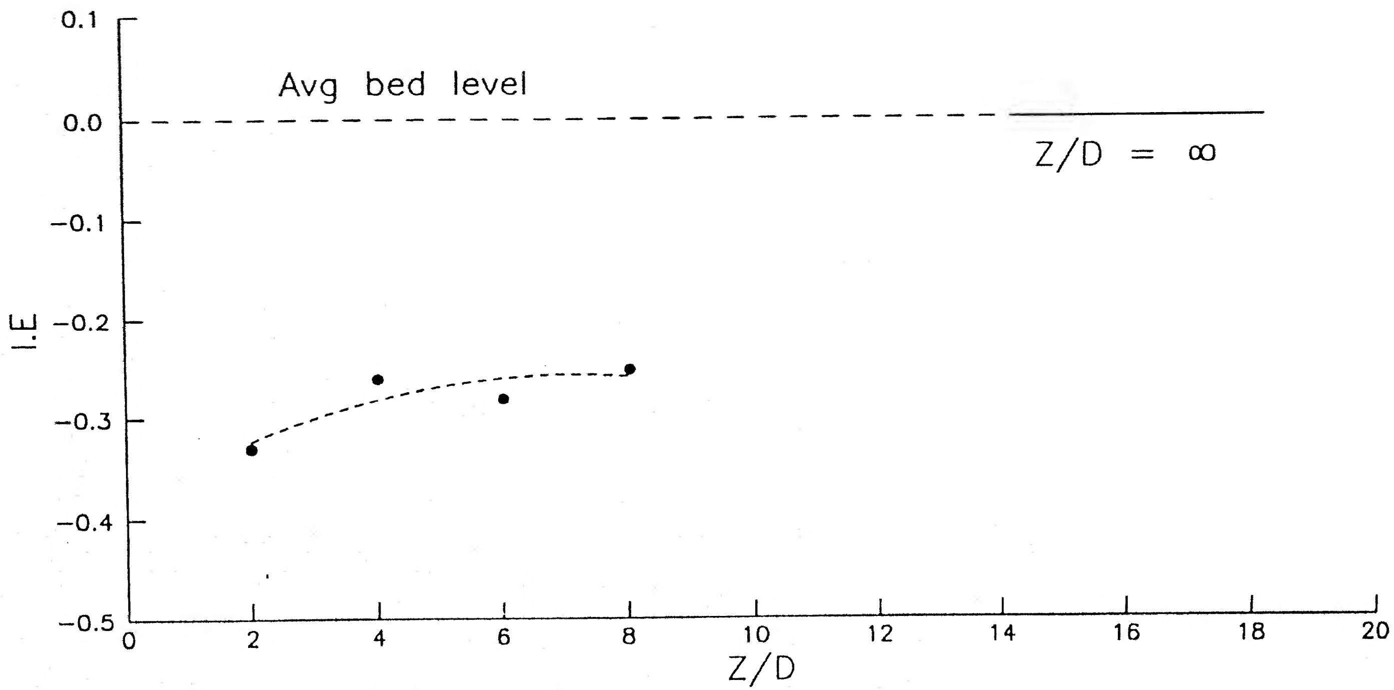


Fig: 4.26
INTERFERENCE EFFECT DUE TO LATERAL SPACING ON MAXIMUM SCOUR DEPTH

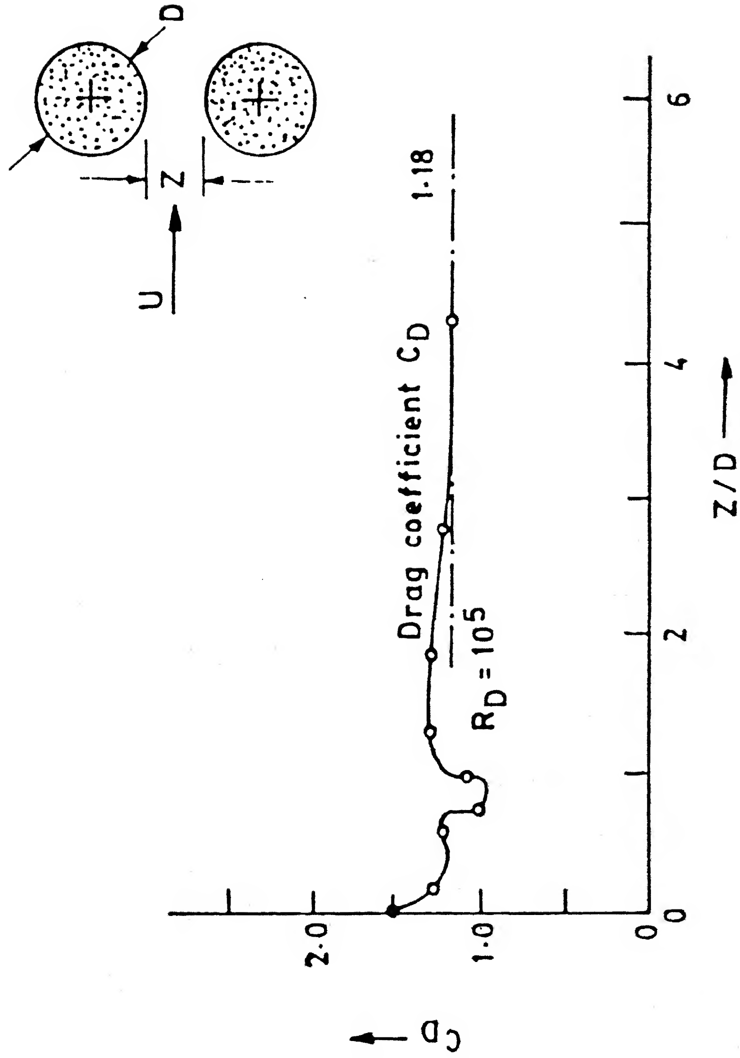


FIG.4.27

Drag of a pair of circular cylinders placed side by side.

CHAPTER - V

CONCLUSIONS

Experiments for the measurement of scour depths were conducted for a period of 600 minutes. Each run was on fine sand, d_{50} = 0.16mm, collected from river Ganges at Kanpur. Three types of pier arrangement patterns namely, tandem arrangement (one behind the other), equilateral triangular arrangement and staggered arrangement were considered. In the staggered arrangement two sub- arrangements are carried. In first arrangement, one pier at upstream and two piers at downstream for different longitudinal and lateral spacing were located. In the second arrangement pattern, two piers were located at upstream and one pier at downstream. The upstream piers spacing were varied between Z/D = 2, 4, 6 and 8. The longitudinal spacing of downstream pier varied from X/D = 1 to 50. In these experimental runs, the velocity was kept very near to the initiation of sediment motion because, this is the state of flow at which maximum scour depths can occur.

The maximum scour depths at the end of 10hrs is plotted for each arrangement pattern. The erosion and deposition of the bed between the piers is also plotted separately for each case.

Interference effect is defined as the ratio of difference of maximum value scour depths between upstream pier and downstream pier divided by maximum scour depths of upstream pier and it is denoted as I.E. The zone of positive value of I.E. and negative value of I.E are shown in each interference figures. The zone of positive I.E values is the zone of less scour

depth of downstream pier. This zone is considered as safe. The negative value of I.E is considered to be dangerous because the downstream pier scour depth is more than the upstream pier. Here the interference effect is to increase the scour depth of the downstream pier. In the tandem arrangement the magnitude of I.E is observed always positive indicating safe zone. In the equilateral triangular arrangement the negative zone occurs when cylinders are closely placed. For higher spacing, I.E is positive, indicating the safer zone. In the case of staggered arrangement, when one upstream pier and two piers located downstream, negative I.E zone occurs around the edge of the upstream pier wake. Positive zone of I.E value occurs dominatingly beyond this upstream pier wake edge. Inside the upstream pier wake zone, the value of I.E is positive. In the case of two piers upstream and one pier downstream, the zone of negative value of I.E, varies with upstream pier spacing. As the upstream pier spacing increases the negative interference zone length increases linearly with lateral spacing. The magnitude of intensity of negative interference decreases with increase in lateral spacing. Effect of lateral spacing on the maximum scour depths of upstream cylinders shows that the magnitude of negative interference is of the order of 0.33 when Z/D = 2, and decreases with increase in Z/D values. Wet paint impression studies are carried out to observe the flow pattern on the rigid plate for different arrangement of cylinders. These wet paint impressions indicate the growth of wake zone behind the cylinders and their merging. This study also reveals the flow pattern in the separation zone where horseshoe vortex is present.

Suggestion for Further Work

Effect of interference on the pier surface pressure distribution and form drag for all arrangements tried should carried out. These effects should be analysed in terms of scour depths.

Effect piers or piles placed in a close proximity on the form drag and on the scour depths needs to be investigated.

Flow visualisation and wet paint impressions should be used to analyse the flow pattern of piles or piers subjected to interference.

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